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Canada-U.S. Workshop on

Frontiers of Quantum Electronics

February 28 to March 1, 1996

University of Toronto, Toronto, Canada

PROCEEDINGS

Canada-U.S. Workshop on *"Pan American S&T" and "Frontiers of Quantum Electronics"* February 28 to March 1, 1996 University of Toronto Toronto, Canada

PREFACE

1. THE WORKSHOP

1.1 ORGANIZATION AND OBJECTIVES

To provide impetus and a forum for the exchange of ideas on how to promote S&T collaborations between Canada and the U.S.A. and other countries on the American continent, the Committee organized a three-day meeting, from February 28 to March 1, 1996, at the University of Toronto, financially sponsored by the Ontario Laser and Lightwave Research Centre on behalf of Technology Ontario and by the U.S. Army Research Office. The meeting had two components: the first was a one-day administrative/planning session attended by senior administrators of the government, industry and academia from Canada, the U.S., Mexico, Chile, Brazil and Argentina. The second component was a technical Workshop on frontiers of quantum electronics and quantum optics that was attended by some 70 leaders of the scientific communities in government, universities and industry from these countries. Altogether there were some 90 participants, many of whom attended both sessions. Many government agencies were represented, including the Department of Energy, the Office of Naval Research, the Air Force Office for Scientific Research, the Army Research Office, the army labs, the NSF, Canada's Ministry of Industry and Ministry of Foreign Affairs and the National Research Council of Canada, Argentina's Academy of Science, Brazil's university at Campinas, the Atomic Energy Commissions of Chile and Mexico, Chile's Conacyt, Northern Telecom, Dupont, Ontario Hydro, and several others.

1.1.1. ADMINISTRATIVE/PLANNING MEETING: AN OVERVIEW

PARTICIPATION, EXPANSION, INTERACTION were key words in this meeting of senior S&T managers from Canada, Mexico, Chile, Brazil, Argentina and the U.S., as well as a number of senior executives from Canadian government and industry. In on-going efforts to expand the scope of international programs and promote interaction among leaders of government and the scientific community and "captains" of industry in the Western Hemisphere, ARO co-sponsored this "Pan-American Initiative in Research Administrative Meeting", held on February 28, and hosted by the University's Office of Research and International Relations. Plans were discussed to achieve this objective of global cooperation and information was exchanged on the current research in these countries in the area of quantum electronics to identify opportunities for collaboration. The ARO was represented by Dr. Gerald Iafrate, Director, Dr. Michael Stroscio and Dr. Iqbal Ahmad. Representing the Canadian scientists were Professor John Polanyi, Nobel Laureate, and Professor Jimmy Xu, Workshop Chair.

Professor Heather Munroe-Blum, Vice President of Research and International Relations, who chaired the meeting, emphasized the need for increased international interactions among scientists and indicated the high level of interest in this initiative on the part of Canadian industry and academia.

R&D: PRESENT AND FUTURE

On the side of government and academia, summaries of current programs aimed at promoting both national and international scientific development were presented by Dr. Gerald Iafrate, on behalf of ARO, by Dr. Nick Bottka of ONR, Col. Jan Cerveny, Director of AFOSR International and Academic Programs, Dr. Lawrence Goldberg of NSF, Dr. Jose Martinez on behalf of DOE, Dr. Miguel Jose Yacaman, Direcor of Mexico's Atomic Energy Commission, Dr. Carlos Brito-Cruz, Vice Rector of the University of Campinas, Brazil, Dr. Mario Mariscotti, President of the Argentina Academy of Sciences, Dr. Eduardo Saravia of the Chile Atomic Energy Commission. Current initiatives, all aimed at expansion and national/international cooperation include the ARO "federated laboratories", government-sponsored university centres of excellence, university fellowships for graduate and post-doctoral research at home and abroad, the Distinguished Lecture program of the ONR-AFOSR, the Pan American Study Institute concept (modeled on the NATO Advanced Study Institute) being developed by DOE in collaboration with NSF and many South American countries. All participants stressed the need for increased scientific cooperation among nations of the Western Hemisphere, with expanded information/technology exchange as a source of help and guidance, particularly for the developing nations of South America.

The Canadian industrial perspective, presented by Dr. Claudine Simson, Vice President of Strategical Technologies and External Research, Nortel, outlined Nortel's present activities in promoting S&T research in North America, South America, Europe, Russia, and Asia Pacific. Through supporting R&D projects, joint ventures and programs in scientific areas such as: broadband networks, wireless, multimedia, hardware and software, and through outreach programs to improve human resources through financial support of education and research, the focus is on providing world-wide access of new S&T developments to Nortel and its affiliates. Dr. Simson applauded the ARO Pan American initiative and offered to support any collaborative activity that might emerge.

Another view, presented by Dr. Douglas Hull, representing the Department of Industry of Canada, stressed technology transition, small business innovation research, information highway and harnessing technology as the keys for improved productivity. From the defense point of view, Col. Ronald Janowsky, Commander of the USRDSG-Canada, highlighted his office's activities in promoting US-Canada cooperation in acquisition as well as development of technologies.

PANEL DISCUSSION

Followed the technical presentations on February 28, moderated by Professor Martin Moskovits, to identify further actions. Professor Moskovits suggested forming an organization similar to the one in the European Community countries, or a federated lab in which selected labs from the Western Hemisphere could participate. The consensus was to start interactions in the Western Hemisphere by first establishing contacts and identifying the opportunities available in each country. To accomplish this, it was decided to form a steering committee to plan future activities.

PAN AMERICAN UNION FOR THE ADVANCEMENT OF SCIENCE AND TECHNOLOGY

In the second planning meeting held on February 29, a working group was formed with Dr. Iqbal Ahmad (US) as Chair, Dr. Claudine Simson and Professors Martin Moskovits and Jimmy Xu (Canada), Dr. Carmin Cisneros and Dr. Miguel Jose Yacaman (Mexico), Dr. Brito Cruz (Brazil), Dr. Mario Mariscotti (Argentina), and Dr. Eduardo Saravia (Chile). Each member of this newly-formed group, PAUAST, would identify his/her country's strong S&T areas and high-priority R&D programs to establish a common basis for future interactions.

1. 1. 2 TECHNICAL SESSIONS: FEBRUARY 29-MARCH 1

In the Workshop following the Administrative/Planning Meetings, a total of 24 technical presentations were made by many of the same participants, academics and senior managers (or their representatives), from all the major countries of the Western Hemisphere. Areas covered were: Laser Spectroscopy and Photochemistry, Photonic Band Gap Engineering, Photonic and Quantum Devices and Applications, Quantum Confinement/Microstructure, Non Linear Optics/Ultrafast Phenomena and Devices, and Materials for Optoelectronics. Enthusiastic audience participation followed in the discussions after each paper, which contributed to making this a very lively and interesting meeting.

There were some 74 attendees, one from Argentina, two from Brazil, one from Chile, 60 from Canada (including many of UofT's most promising graduate students and post-docs who maximized this valuable opportunity for exchanging information and establishing international contacts), two from Mexico and eight from the U.S. This was indeed a unique and distinguished gathering of luminaries from academia, including UofT's own Nobel Laureate, Professor John Polanyi, prominent government officials such as Dr. Gerald Iafrate, Director of the US Army Research Office, the director of Mexico's Atomic Energy Commission, Dr. Miguel Jose Yacaman, and industrial leaders such as Nortel's Vice President, Strategical Technologies and External Research, Dr. Claudine Simson.

A name list of participants and presentation titles are given in the Workshop Proceedings.

1.2 ACHIEVEMENTS AND CONCLUSIONS

One of the most important aspects of this Workshop is that it brought together scientists from Canada, U.S.A., and South America with those from US Federal agencies, thereby sowing the seeds for future interaction. Through the technical sessions, the presentations and the evening panel discussions, delegates explored areas of mutual interest and identified schemes to promote interactions among scientists, engineers and educators in Pan American countries to foster further specific actions and to keep the momentum going. A new institution was formed and named *"The Pan American Union for the Advancement of Science and Technology"*. An executive committee with representatives from each country was elected and charged with the responsibility of planning future actions and further gatherings. The tentative composition of the executive committee members is as follows: Dr. Iqbal Ahmad of the U.S. Army Research Office, Dr. Larry Goldberg of the U.S. NSF, Dr. Nick Bottka of the U.S. Office of Naval Research, Dr. Joe Martinez of the Department of Energy, Dr. Mario Mariscotti representing Argentina, Dr. Brito Cruz representing Brazil, Dr. Eduardo Saravia representing Chile's Conacyt, Dr. Jose Yacaman representing Mexico, and Colonel Jan Cerveny, Professor Martin Moskovits, Professor Jimmy Xu and Dr. Claudine Simson representing Canada.

The main achievements of this meeting are as follows:

First, and perhaps most important, is that there is an increased enthusiasm and hope for cross-continental collaboration on the fronts of science and technology that complements the planned or ongoing initiatives on the educational front.

Second, the meeting helped identify some of the key elements that bind all the parties together and possible actions that can be taken by governments and by individuals to promote science and technology for the common interest in the health of all the economies and to reduce the great disparity between the highly advanced countries and the less developed countries in science and technology. Compelling cases were made by delegates from Latin America and Mexico, one being that since all the countries are undergoing drastic changes in economic policies and moving towards developing export-oriented economies, the demand for domestic supply of scientific and technological expertise and know-how is ever greater. Nonetheless, the supply of such expertise is severely limited for a number of historical reasons. Examples of such limitations were cited, among which some of the numbers are quite striking. For instance, the numbers of scientists and

engineers per million of population in the U.S. and Canada is about 2,700 whereas in Latin America, it is 200. Not uncoincidentally, the projected GDP between North America and Latin America has a similar ratio of 10 to 1. It is the consensus that for economic growth in Latin America to advance toward export economy, it must be accompanied by advancement in science and technology domestically, and international cooperation would be essential to accelerate the development process of the necessary domestic expertise and the mass to the size that is compatible with the economic growth and demanded by the economy. For example, in Mexico, there is a diverse system of higher education, yet there is still a pressing demand to be met in bringing more of their faculty to the Ph.D. level through advanced research. It was also recognized that cooperation in science and technology would be beneficial to North America's industry. This is not only from the point of view of the trading dimension, but also from the point of view of human resources. Multi-national corporations are now constantly hiring graduates of colleges and universities in all of these countries. Therefore, enriching faculty and strengthening research programs consititute the best approach for the training of highly qualified personnel. Another illuminating case was made at the meeting: European communities have been introducing in South America a number of active and highly effective programs for collaborations in science and technology for about 5 years. Previously, almost all the research instruments and facilities in the labs were products of North America - primarily, the U.S.A. Now, however, in many places one sees that nearly 50% of the instruments and new equipment were purchased from Europe, largely a result of the North American researchers' staying in a European lab for an extended period and becoming accustomed to the research facility at that particular place. The Pan American corporation represents a new dimension and also offers a new exciting opportunity: the potential to now establish research consortia and networks similar to the ones established by the European Commission in the European countries to gather the complementary expertise, pool the resources and coordinate multi-disciplinary and multi-team research effort on some "big" problems. It is hoped that such cooperative efforts will be less subject to the changes of policies and directions of one nation's government agencies.

The third important achievement of this meeting is that individually, delegates fostered new linkages and planned new collaborative actions with one another. This was a result of the presentations, discussions and exchanges of ideas on the technical fronts summarized in the Proceedings. It was the hope of the Committee that this meeting would be remembered as one of the first steps: a new form of development of science and technologies in this continent.

2. FOLLOW-UP EVENTS

2.1 COMMITTEE MEETING OF THE PAN AMERICAN UNION FOR THE ADVANCEMENT OF SCIENCE AND TECHNOLOGY, CANCUN, MEXICO, SEPT. 2, 1996

A meeting of the Committee that evolved from the Administrative/Planning Sessions of the Workshop was held in Cancun the following September. After welcoming remarks and outline of the Agenda by Professor Jose Yacaman and Dr. Iqbal Ahmad, a report on the Toronto meeting was presented by Professors Jimmy Xu and Martin Moskovits. A report of PAUAST activities in the interval between March and September was presented by Dr. Ahmad, and a discussion of the proposed PAUAST Constitution - its aims and objectives, structure and technical program - followed a presentation by Prof. Moskovits and Dr. Ahmad.

2.2 OPPORTUNITIES OF PAN AMERICAN COOPERATION IN SCIENCE & TECHNOLOGY, CANCUN, MEXICO, SEPT. 3, 1996

A meeting, chaired by Professor Jose Yacaman, was held for further discussion of the Pan American Initiative, specifically, to identify the areas, programs and opportunities for international scientific collaboration in each country. After welcoming remarks and introduction by Prof. Yacaman, comments about the Pan American Inititiave by Dr. Ahmad and Prof. Xu, a status report on the AAAS Symposium of "Science and Technology in the Americas" was presented by Prof. Gerardo Boeno Zirion of the Foundation Mexico-Estados Unidos para la Ciencia, Mexico. A report on Mexico's Conacyt International S&T Program was presented by Dr. Sylvia Ortega, Director General Int'l, Conacyt. Presentations followed, outlining the various countries' perspectives on potential opportunities for international S&T collaboration, with Prof. M. Moskovits representing Canada, Prof. Hugo Fragnito, Brazil, Dr. H.A. Videla, Argentina, Dr. E. Saravia, Chile. The perspectives of various US federal agencies were also presented by: Dr. Al Harvey (NSF), Dr. Nick Bottka (ONR), Dr. John Mann (AFOSR), and Dr. I. Ahmad (ARO).

3. ACKNOWLEDGMENTS

The Organizing Committee wishes to thank all those who donated their time, interest and efforts to make this a significant, valuable and productive meeting; first, the co-sponsors, the U.S. Army Research Office and the Ontario Laser and Lightwave Research Centre for their vision in enabling such a meeting through financial, administrative and logistical support; second, the University of Toronto's Office of Research and International Relations, under the direction of Professor Heather Munroe-Blum, for their key role in organizing and hosting the Administrative/Planning Meetings which preceded the technical sessions. Last, but perhaps most importantly, we'd like to thank all the members of the scientific research/technology community who came together to share, exchange, listen and discuss; the speakers who travelled here, some from great distances, to present their recent research achievements and on-going research programs at the forefront of quantum electronics in education, government and industry; in summary, all who participated in pursuing the common goal of action, interaction and exploring the potential for national and international scientific collaboration.

J.M. Xu
Workshop Chair

and Committee Members: Peter Smith, Sajeev John

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Many-body Effects and Density Functional Formalism in Nanoelectronics

Gerald J. Iafrate
U.S. Army Research Office
Research Triangle Park, North Carolina

Nanoelectronics is the integration of molecular-sized electronic switches with photonics and phononics to produce logic functional and sensing capabilities heretofore not realizable with conventional technology. In establishing nanoelectronics as a viable molecular electronics technology of the future, many new and interesting questions emerge concerning the physics and electronics on the submicron and ultrasubmicron dimensional scale, notably the role of quantum, many-body effects. Several key nanostructures under study in nanoelectronics sustain high electron densities in molecular-sized volumes; in such structures, many-body effects such as exchange and correlation, which arise from the Pauli Exclusion Principle, become non-negligible, and in fact, may dominantly influence the electronic response characteristics.

In this presentation, a methodology is presented for including many-body effects in nanoelectronic structures through the application of density function theory. A local, spin-polarized, exchange-only potential, derived from an Optimized Effective Potential (OEP) consideration, is presented, and is shown to be a remarkably accurate representation of the non-local, self-consistent, Hartree-Fock potential. This potential is shown to be related to the well-known Slater-exchange potential through an additive shift in the usual, orbital-dependent, single particle Hartree-Fock potentials by a set of self-consistently determined constants. In addition to resulting in remarkably accurate total energies for atoms, the potential under consideration goes over to the Kohn-Sham potential in the limit of slowly varying density, thus reconciling a long standing discrepancy concerning the appropriateness of the prefactor of the "Slater" exchange-only potential.

Further, as derived from the Density Function Formalism, the capacitance of an N-electron system is discussed, showing the atomistic connection between the capacitive energy, the ionization potential, and the electron affinity of the charged system; it is shown that this connection leads to the linkage of the capacitive energy to the difference between the lowest unoccupied and the highest occupied Kohn-Sham orbital energies of the system. An illustrative example is given to show explicitly the microscopic behavior of the derived capacitance for a finite electron system, and to discuss the tendency of the derived capacitance to limit toward the classical electrostatic capacitance as the system becomes macroscopically large.

PHOTOCHEMISTRY IN THE ADSORBED STATE; Using Light as a Scalpel, and a Crystal as Operating Table.

John C. Polanyi
Department of Chemistry, University of Toronto.

Interest in the molecular motions in chemical reactions (called 'reaction dynamics') has led in recent years to a new field of chemistry in which molecules are aligned and positioned at a crystal surface before a reaction is triggered by a laser pulse; this is *photochemistry in the adsorbed state.* In a variant of this approach the species being photolyzed is a gaseous complex between a metal (that takes the place of the crystal) and a loosely attached molecule (that takes the place of the adsorbate).

In both types of experiment the light can cause an electron to jump from a metallic or semi-conducting substrate to the adsorbate, whereupon the latter dissociates and/or reacts with the metal. This has been called 'photoinduced harpooning', in which the harpoon is the electron and the fish being speared and hauled-in, is the adsorbed molecule. It is a particularly simple type of reactive process, rendered still simpler by the alignment and positioning of the reacting species. An incidental consequence of this type of 'catalyzed photochemistry' is that photolysis can be shifted from the ultraviolet to the visible, where the sun's rays can cause the process to occur.

However, the principal interest of this basic science in terms of application at the present time is to nanoscale switching and charge-transfer processes. This is being pursued in the speaker's laboratory with the aid of Scanning Tunneling Microscopy which permits the photoeffects to be observed directly at the molecular level. An example, given in this talk, is the controlled photoremoval of atoms from the surface of Si(111)7×7 recently explored here.

BIOGRAPHY — JOHN CHARLES POLANYI

John Polanyi, educated at Manchester University, England, was a postdoctoral fellow at Princeton University, U.S.A. and the National Research Council, Canada. He joined the University of Toronto, Canada, in 1956. His research is on the molecular motions in chemical reactions in gases and at surfaces. He is a Fellow of the Royal Societies of Canada (F.R.S.C.), of London (F.R.S.), and of Edinburgh (F.R.S.E.), also of the American Academy of Arts and Sciences, the U.S. National Academy of Sciences and the Pontifical Academy of Rome. He is a member of the Queen's Privy Council for Canada (P.C.), and a Companion of the Order of Canada (C.C.). His awards include the 1986 Nobel Prize in Chemistry (shared), the Royal Medal of the Royal Society of London and some thirty honorary degrees from six countries.

He has served on the Prime Minister of Canada's Advisory Board on Science and Technology, as Foreign Honorary Advisor to the Institute for Molecular Sciences, Japan, and as Honorary Advisor to the Max Planck Institute for Quantum Optics, Germany. He is presently on the Board of the Steacie Institute for Molecular Sciences, Canada, the Board of the Premier's Council of Ontario, and co-chair (with Sir Brian Urquhart) of the Department of Foreign Affairs International Consultative Committee on a Rapid Response Capability for the United Nations.

He was a founding member of both the Committee on Scholarly Freedom of the Royal Society, and an international human rights organization, the Canadian Committee for Scientists and Scholars, of which he is the current President. Additionally he was the founding Chairman of the Canadian Pugwash Group in 1960, and has been active for 35 years in International Pugwash. He has written extensively on science policy, the control of armaments, and peacekeeping. He is co-editor of a book, "The Dangers of Nuclear War".

COHERENCE & INTERFERENCE IN ATOMIC SYSTEMS: GAIN, INDUCED-TRANSPARENCY & STIMULATED EMISSION

Boris P. Stoicheff
Department of Physics, University of Toronto, and Ontario Laser & Lightwave Research Centre.

Considerable discussion has taken place recently on the possibility of achieving amplification and stimulated emission without population inversion. Following a brief review of the concept of strong electromagnetic-coupling of states, experiments will be presented using a variety of atomic media to demonstrate the properties of the resulting emission. While it has been possible to generate intense beams of coherent radiation in the visible and far-ultraviolet regions, the question still remains; "will useful sources of stimulated emission be realized in this way?"

B. P. STOICHEFF BRIEF BIOGRAPHY

BORIS STOICHEFF is an Emeritus University Professor of Physics at the University of Toronto, and the founding Executive-Director of the Ontario Laser and Lightwave Research Centre. Before joining the University in 1964, he was a Research Officer in the Physics Division of the National Research Council, in Ottawa. His research interests include light, spectroscopy, lasers, and their applications in Physics. He built Canada's first lasers in late 1960, while at NRC. His interests in Quantum Optics and Nonlinear Optics include stimulated Brillouin and Raman scattering, 2-photon spectroscopy, and generation of tunable far-ultraviolet radiation for atomic and molecular spectroscopy.

He received a B.A.Sc. in Engineering Physics in 1947 and a Ph.D. in Molecular Physics in 1950, at the University of Toronto. His service on national and international committees is extensive and varied. It includes membership on the Council of NRC, the Quantum-Electronics Council; the Council of Professional Engineers of Ontario; the Ontario Nuclear Safety Review Committee, Presidency of the Canadian Association of Physicists (1984), and Presidency of the Optical Society of America (1976). He is an Officer of the Order of Canada, a Fellow of numerous Societies including, The Royal Society of London, and The Royal Society of Canada, and Foreign Honorary Fellow of the American Academy of Arts and Sciences, the Indian Academy of Sciences, and the Macedonian Academy of Sciences and Arts, . He has supervised the research of students leading to 22 MSc. and 24 PhD degrees.

CANADA-U.S. WORKSHOP ON
FRONTIERS OF QUANTUM ELECTRONICS

Sajeev John
Department of Physics
University of Toronto

Photonic Band Gap Materials: A New Frontier in Quantum Optics

Abstracts

Since the invention of the laser, the field of photonics has progressed through the development of novel engineered materials capable of processing light in novel ways and coupling it to electronic devices. The invention of photonic band gap (PBG) materials has opened a new frontier in the engineering of such materials. It has opened the possibility of new functionalities such as narrowband or broadband wavelength rejection, suppression of spontaneous emission, ultra-small high Q optical cavities, high efficiency microlasers, and low threshold optical bistability for optical switches. In this talk, I describe ways in which PBG materials represent a new frontier in fundamental science in which atom-cavity mode coupling as well as atom-atom couplings are strong compared to damping rates. This leads to novel phenomena such as photon-atom bound states, lasing without a cavity mode near a photonic band edge, quantum optical spin-glass state of impurity two-level atoms, and other collective phenomena. In addition to suppression of spontaneous emission, certain propagative effects are preserved in a PBG. This distinguishes PBG systems from conventional microcavities used in studies of quantum electrodynamics.

Sajeev John

Biography

Prof. Sajeev John received his Bachelor's degree from M.I.T. and his Ph.D. from Harvard, in 1984, in theoretical condensed matter physics. He was an NSERC postdoctoral fellow at the University of Pennsylvania for 2 years before joining the faculty of Princeton University in 1986. While an Assistant Professor at Princeton, he was also employed as a Laboratory Consultant to Exxon Research and Engineering and to Bell Communications Research. In 1989, he joined the senior faculty at the University of Toronto.

Dr. John wrote pioneering papers on the subject of photon localization in 1984 and the subject of photonic band gaps in 1987. These subjects continue to be active area of research today. His current interests include quantum optics, high temperature superconductivity and bio-medical optics.

EFFECT OF THE PHOTONIC BAND EDGE ON SPONTANEOUS EMISSION FROM MULTILAYER SEMICONDUCTOR DEVICES

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and

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We present results of an experimental investigation into alteration of the spontaneous emission spectrum of GaAs from within one-dimensional photonic band gap (PBG) structures. The PBG samples are multilayer $AlAs/Al_{0.2}Ga_{0.8}As/GaAs$ *p-i-n* light emitting diodes, with layers arranged as a distributed Bragg reflector. The emission spectra normal to the layers are measured, and we use a novel method to model the power spectrum of spontaneous emission from within the structures. We find that the emitted power is enhanced by a factor of 3.5 at the frequencies near the photonic band edge.

A generic PBG material is defined as a periodic structure that does not allow propagation of photons over a finite band of frequencies. A one-dimensional PBG structure, when restricted to a quarter-wave stack, is called a distributed Bragg reflector (DBR). One-dimensional PBG structures have been shown to exhibit interesting effects at the photonic band edge such as enhanced gain[1] and anomalous group velocity and dispersion[2]. The presence of a three-dimensional PBG structure has also been predicted to alter the fluorescence[3] and emission[4] characteristics of a nearby emitting material. In the present study, we investigate the change in the power spectrum of spontaneous emission due to the placement of emitting dipoles within a finite one-dimensional PBG structure. Our group has recently addressed this problem theoretically using a numerical model[5], showing that the power radiated by dipole oscillators can be strongly enhanced at frequencies near the photonic band edge. For frequencies inside the photonic band gap, the emitted power was found to be greatly suppressed. Similar effects have been predicted by Suzuki and Yu for a three-dimensional PBG[6], using a method developed by Dowling and Bowden[7].

In order to experimentally verify such theoretical findings, we used three samples. A three-layer, AlGaAs/GaAs/AlGaAs, *p-i-n* light-emitting diode was used as a reference sample. Each of the three layers in the reference sample had an optical thickness greater than the vacuum wavelength of the spontaneous emission from GaAs (~875nm). The emission spectrum from the GaAs reference sample was measured, and it was found to be a good emitter over the range of wavelengths from 820--900nm. The two test samples were composed of 20 period

DBR stacks of AlAs/AlGaAs having a single, quarter-wave thick, GaAs emitting layer in the center. One of the structures, Sample A, was designed so that the long-wavelength edge of its high-reflectance band gap coincided with the emission range of the GaAs reference sample. The other structure, Sample B, was designed so that the region of high reflectance (the photonic band gap) overlapped almost completely with the surface emission spectrum of GaAs. The reflectivity spectrum of the GaAs reference sample was essentially flat. We expect Sample A to have its spontaneous emission greatly enhanced and Sample B to have its emission greatly suppressed.

Using a photoresist liftoff process, we patterned annular electrodes into the superstrate contacts on the test samples. With a second, aligned photoresist mask, we wet-etched a square mesa (450 microns on a side) around each of these electrodes. The mesas were wet-etched to a depth of 1.7μm. We used a standard wafer probe to contact the electrodes. Surface emission spectra of the LEDs were obtained under DC forward bias. We measured the power spectra using a monochromator and CCD. The radiation from the surface of each sample was collected with a microscope objective. We corrected the spectral measurements for the response of the lenses, monochromator, and CCD. We recorded spectra for several injection currents. A range of angles (0^o to 15^o) of emitted radiation was collected in the spectrum measurements.

Measured spectra from Samples A and B show that the total integrated emitted power from Sample A is much greater than that from Sample B. They also showed that sample A had two peaks in its emission: the first at the wavelength of peak emission from the GaAs reference sample, and the second at a wavelength corresponding to the long-wavelength photonic band edge of Sample A. The measured emission spectrum from Sample B showed only a single small peak at a wavelength corresponding to the short-wavelength photonic band edge of Sample B. We found that changing the injection current used in each sample (from 24mA to90 mA) did not significantly change the features of the emission spectrum. The fact that the emission of sample A is enhanced greatly compared to that of Sample B over this wavelength range was evident. This is the main result of this communication. In addition, the measured and calculated values of the spontaneous emission enhancement were found to agree very closely. We used a new method for the calculation of the spontaneous emission enhancement: one that is very simple to implement, and very fast to run on an average personal computer.

To summarize, we measured and calculated the enhancement and suppression of spontaneous emission due to confinement of a GaAs emitting layer inside a one-dimensional photonic band gap structure[8]. The results show an enhancement of almost four times the `bulk' emission rate near the photonic band edge and a suppression of nearly twenty times inside the photonic band gap. To our knowledge this is the first experimental verification of enhanced spontaneous emission at the photonic band edge in any dimension. Our experimental results should also be indicative of what to expect in the way of 3-D emission enhancement[6]. The effect of enhancing the spontaneous emission over a desired

range of frequencies in a direction normal to the surface has immediate potential applications in the fields of low-threshold lasing[9] and low power-consumption flat-panel displays[10].

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Photonic Bandstructures for Guided Modes in Semiconductor Waveguides

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Summary

We have developed fabrication and optical probe techniques suitable for studying two dimensional (2D) photonic bandstructures in semiconductor waveguides. The motivation for this research can be appreciated from two perspectives; i) as an extension of a more general class of photonic bandstructure research into a technologically relevant host material, particularly one in which electronic resonances can be brought in tune with strongly dispersive parts of the photonic bandstructure, and ii) as an extension of one dimensional (1D) distributed feedback laser (DFB) grating technology to 2D and to structures possessing a high refractive index contrast. Such structures should serve as micro laboratories in which to study strongly coupled electron-photon physics, and as a test bed for several potential electro-optic device applications.

The fabrication strategy is based on using electron beam lithography (EBL) to define 2D periodic or quasi-periodic lattices in an etch-mask spun on top of a semiconductor waveguide structure. The lattice constant one can achieve with this technique is limited primarily by the etching technique used to transfer the pattern from the mask into a lattice of "holes" extending partially through or completely through the waveguide layers. We have so far limited ourselves to wet chemical etching techniques, which work well down to at least ~ 400 nm lattice constants. Dry etching technologies would allow smaller lattice constants to be achieved.

In a previous report of a 2D patterned semiconductor waveguide [1] for photonic applications, the refractive index lattice was located on top of an asymmetric waveguide. In order to maximize the refractive index modulation felt by the guided modes, we have adopted a symmetric approach in which a 2D lattice of holes is etched completely through a symmetric, *air-bridged* waveguide. The result is a 2D porous semiconductor wafer, ~ 120 nm thick, ~ 80 μm square, supported on three sides by the substrate.

The immediate objective is to have the texture induce modifications of the guided mode dispersion over as large a spectral range as possible (towards a true optical bandgap *for guided modes*). To demonstrate these effects requires a broadband (several thousands of wavenumbers) spectroscopic probe suitable for selectively studying very small structures. We have therefore developed a fibre-based "white-light" excitation source, which when used in conjunction with a

variable-geometry imaging system coupled to a Fourier Transform Spectrometer, allows us to probe the spectrum of light reflected and scattered from the air-bridged waveguides.

The figure shows the TE (peaked) and TM (weak) polarized components of the light emitted from a cleaved edge of the porous waveguide, in the basal plane, when the white light was incident normal to the plane of the guide (essentially a normal incidence grating coupling geometry). In this 90 degree scattering geometry, phase matching occurs in the vicinity of the even order band gaps in the direction normal to the cleavage plane (which is parallel to the [10] direction of our square lattice). These data, together with others taken in different scattering geometries, suggest that the second order gap in this structure is on the order of 12% of the centre frequency.

These initial results on guided mode photonic bandstructures are very encouraging, and more work on different lattice types, and with different optical probes is in progress.

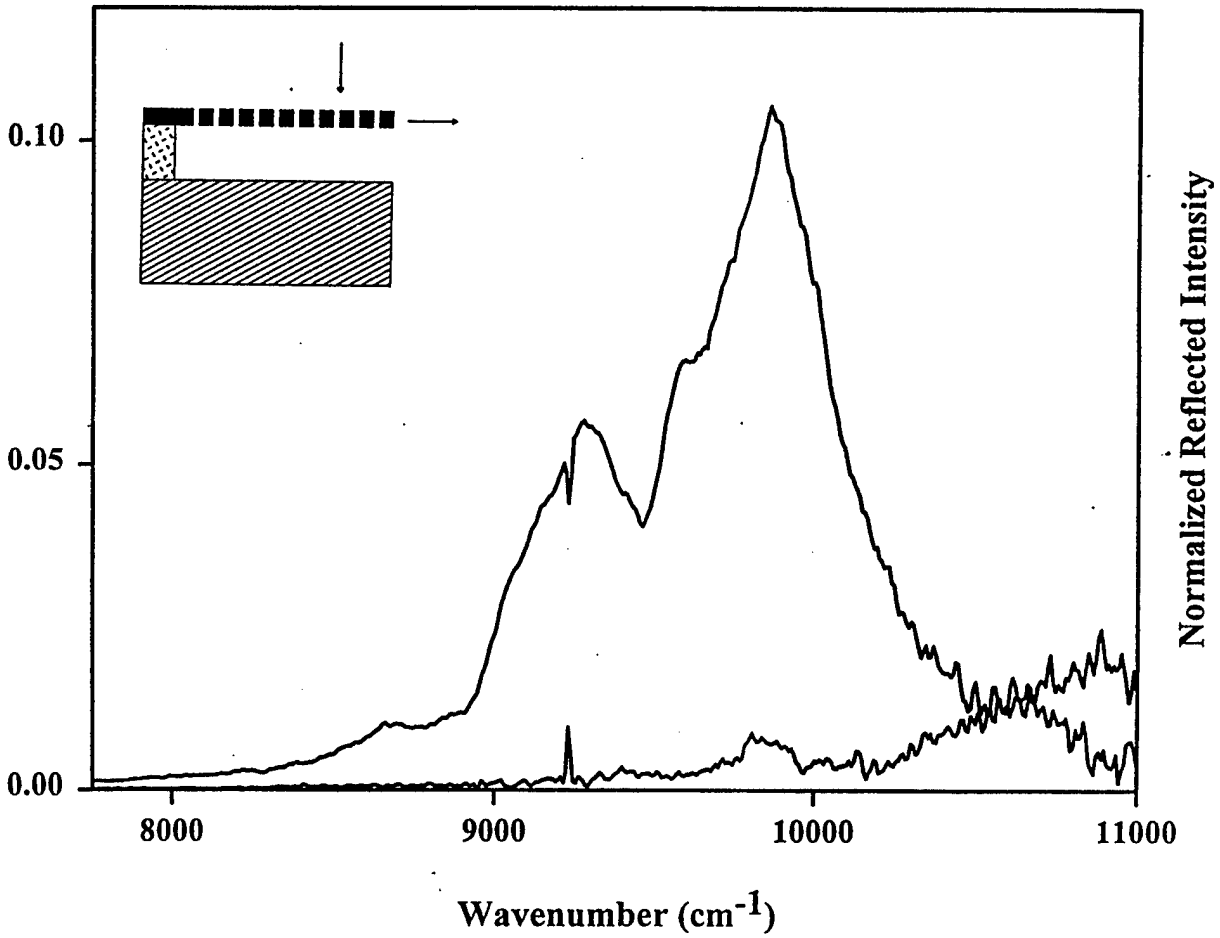

Figure 1: The normalized scattered light spectrum collected from the cleaved edge of a square, 2D photonic lattice with a 480 nm lattice constant. The excitation was incident normal to the AlGaAs/GaAs/InGaAs waveguide (see insert).

Acknowledgements: We wish to thank Shane Johnson and Tom Tiedje for growing the waveguide structure, as well as NSERC and Rogers Cable TV Limited for financial support.

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Worked at NRC in Ottawa for 9 years, ending up as senior research officer and Group Leader of the Quantum Transport Group in the Institute for Microstructural Science. Worked on dynamical properties of semiconductors and heterostructures: time-resolved Raman from hot phonons/plasmons, tunneling rates of electrons and holes, many-body screening effects in nonequilibrium systems etc.

Moved to UBC in 1993

Have partially established, and am continuing to set up a nanostructure fabrication capability for photonic and electronic studies. Efforts so far have been focussed on fabricating and studying the optical properties of photonic bandstructures in waveguides, and in quantifying screening and correlation effects on the absorption of light in 2 dimensional electron gases.

Advances on the Front of Optoelectronic Integration

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The optoelectronics laboratory at the University of Toronto currently conducts theoretical and experimental research in three areas: (i) Quantum and optoelectronics devices, (ii) Quantum physics & materials, and (iii) Optoelectronic Integration.

In this summary, I outline some of the recent advances we have made on the front of optoelectronic integration. In particular, I'll focus on the following topics:

– Lateral Current Injection Lasers;
– Feasibility of integrated lasing, amplification and wavelength division multiplexing;
– OEIC design and modeling tools (OE^{UT} – SPICE and FELES).

Parts of these projects have been supported by and carried out in close collaboration with Bell-Northern Research Ltd., NRC of Canada, and GeeO of France, respectively; and have received continuous support from NSERC, Technology Ontario, and other research organizations in USA and Japan.

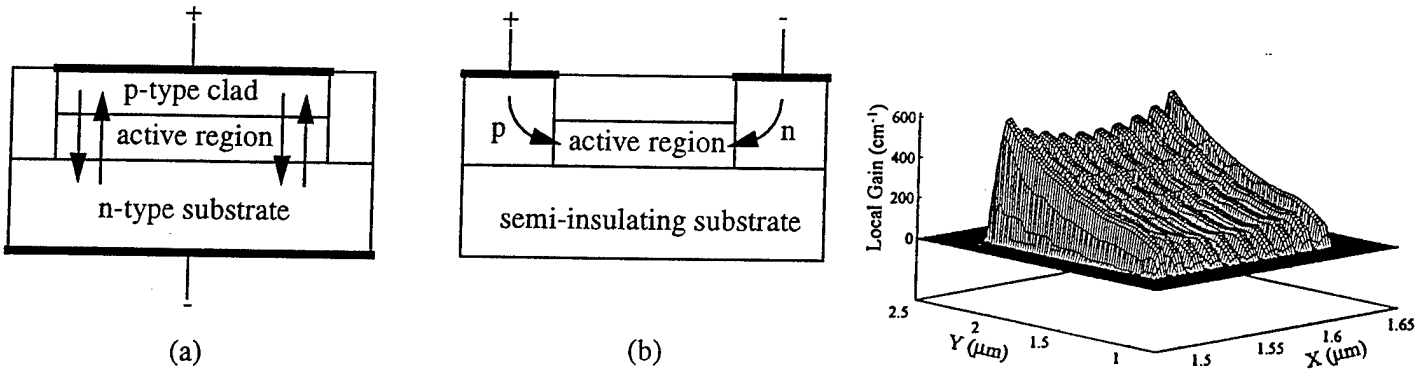
LATERAL CURRENT INJECTION LASERS

In comparison with the evolution of electronic devices, semiconductor laser development has been one-sided, nearly all efforts falling into the category of vertical injection. However, vertical injection lasers, with contacts on the top and bottom and highly doped substrate and cladding layers, are intrinsically unsuited to integration with other devices on a single substrate and suffer high parasitic delay in response and high parasitic loss. Still worse, they are subject to a number of design and material constraints imposed by the need of facilitating the vertical injection of current. For example, the optical design is coupled to the electrical design, leading to compromised performances in both aspects. Another example of the drawbacks of the vertical injection scheme can be found in the case of implementing DFB in a laser where the vertically injected current has to pass through the etched-then-regrown grating interface, imposing an exceedingly high demand on the quality of the regrowth.

Lateral current injection lasers with both contacts on the top surface of a semi-insulating substrate are natural candidates for OEICs and for high speed operations. Despite the compelling advantages, previous lateral injection efforts have been largely empirical, treating the new geometry and configuration as a perturbation to the vertical injection paradigm.

Overall, this front of development has not benefited at all from the same cycle of physical analysis, informed creativity, quantitative design optimizations, and experimental validations.

Through a multi-year investigation, both theoretically and experimentally, we have gained insight into some of the physical mechanisms which govern the performance of this class of lasers. And, we have shown that by releasing the vertical degree of freedom relative to conventional vertical injection lasers, the lateral injection scheme could enable new functionalities such as gain-modulation via a third terminal on the top or capacitive modulation via a FET–like side gate [1-4]. Additional advantages are expected: reduced electrical capacitance, decoupled electrical and optical designs, reduced free carrier induced chirp, improved injection uniformity across the MQWs, and thus improved modal gain.
More importantly, perhaps, we show that lateral injection lasers differ fundamentally from the vertical injection case and demand re-examination from first principles.



Schematic depiction of carrier flow under (a) vertical and (b) lateral injection.

One of the intrinsic differences we found is that the local gain profile can often be highly asymmetric laterally, with its peak normally positioned close to the p-contact region. Physically, this is because of the mobility disparity between electrons and holes which is inherent in most semiconductors. This undesired asymmetry in gain profile together with the desired symmetry in optical mode lead to a number of negative consequences in device performance: higher threshold, smaller slope efficiency, reduced stabilities, etc.

However, this seemingly inevitable problem associated with properties inherent to the materials can be alleviated or even eliminated, as we have found in various experiments and analyses. One way is by engineering the dopant profiles; another is by adding current guiding barrier layers; and yet another is, of course, through the use of strain and strain compensation. A second intrinsic difference we found between the lateral and vertical lasers is that the lateral laser can have a bias-dependent optical confinement factor in the lateral dimension, which increases with current. This gives rise to an improved differential modal gain relative to that of the vertical injection lasers. Moreover, this improvement is accompanied with a reduced differential modal index, and together they make the lateral injection lasers more suited for low chirping applications.

In summary, our findings so far can be stated as follows: There are a number of differences between the two classes of lasers - vertical and lateral; some are intrinsic to device operation mechanisms, some are enabling novel functionalities and new device designs, all necessitate the adoption of a first-principle approach in order to realize the tremendous potential of these OEIC-enabling lateral injection lasers.

INTEGRATED LASING, AMPLIFICATION AND WAVELENGTH DIVISION DEMULTIPLEXING

Lasing, amplification and WDM are all essential for a fully integrated optical device. However, these components are usually implemented in discrete forms in different material systems.

It is desirable and indeed, our aim in this project, to implement all these components in the same material and thereby, to assess the feasibility of integration. To this end, one could choose either a suitable semiconductor or a doped glass waveguide. Here, we focus on the option of the doped glass, mostly because we are also interested in performing a proof-of-concept demonstration for a new WDM device, named Supergrating WDM (or Superimposed Gratings WDM) [5-6]. With the experimental facilities readily available to us at the moment, it is much easier to do this in glass than in semiconductor. To implement the same supergrating concept in semiconductor by etching techniques, we feel that the binary optics designs will be necessary, but not our preference at this early proof-of-concept stage.

As a first step, a low-loss waveguide in a glass host containing a small percentage of rare-earth is fabricated using an ion-exchange technique that was optimized over several years in our collaborator's lab (GeeO, France). For amplification and lasing, neodymium and erbium co-doped with ytterbium are chosen. Neodymium has a strong absorption at 800nm and a strong transition at 1055nm which terminates at a level above the ground state. The erbium transition at 1530nm terminates at the ground state and therefore has an absorption band which must be overcome to reach a net gain. On the other hand, the lifetime of the excited state

is much longer in erbium making it a better candidate for stimulated emission. To increase the otherwise modest absorption at 980nm, the erbium is co-doped with ytterbium, in which system the energies absorbed by ytterbium ions are transferred to the erbium ions. For enhanced photorefractivity under the illumination of a KrF excimer laser, uniform germanium doping is incorporated into the silica glass.

To date, we have succeeded in achieving lasing and amplification in both neodymium doped and erbium/ytterbium co-doped waveguides [7]. For the former with a 71% reflectivity of the mirrors at 1054nm and 5% at 800nm, a lasing threshold of ~8mw pumped at 797nm and a slope efficiency of 13% are obtained in 38mm long 3wt-% neodymium-doped phosphate glass. For the latter, a 2% erbium by weight and 4% ytterbium were doped into phosphate glass. Lasing operation at 1549nm with a slope efficiency of 16% and a threshold of 67mW is observed, pumped at 980nm using a 98.4% over 50nm mirror on one facet and a 20% mirror on the other facet.

The first attempts on proof-of-concept demonstrations of new WDM devices in Ge-doped silica glass waveguides were successful as well [8-9]. The WDM functionality is achieved via superimposing multiple sets of gratings in a planar waveguide.

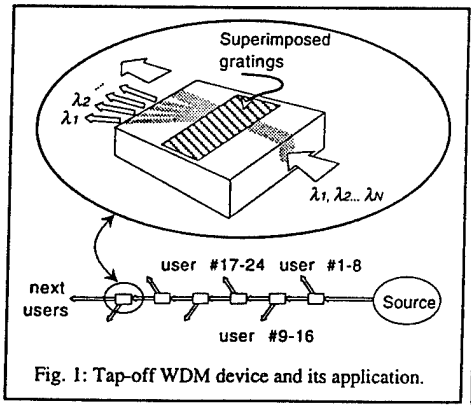


Fig. 1: Tap-off WDM device and its application.

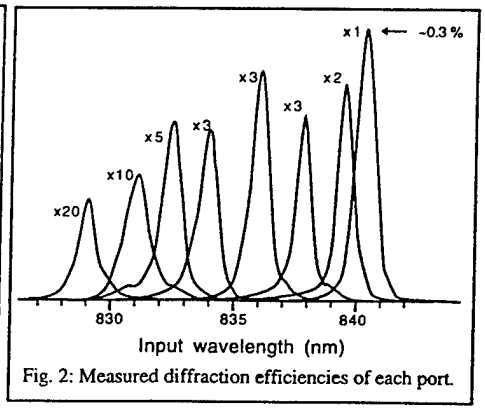


Fig. 2: Measured diffraction efficiencies of each port.

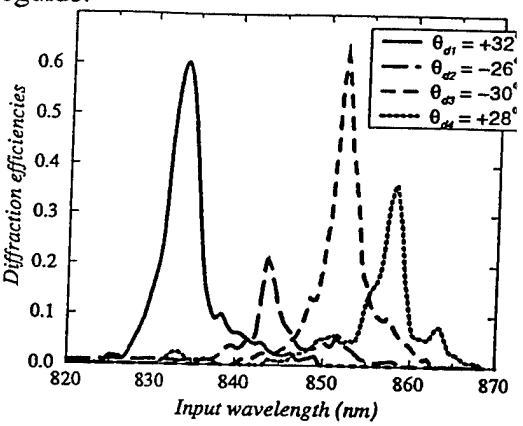


Fig. 4. Diffraction spectra of the 4-channel WDM.

As aforementioned, the gratings can be implemented either by photo-inscription (photorefractivity) or etching. In our particular case, the approach of photo-inscription, into Ge-doped silica by KrF excimer laser and into LiNbO by Argon laser, was used. To increase the waveguide's photosensitivity to the 249nm KrF light, the Ge-doped silica waveguides were put through a pre-treating process of high pressure hydrogenation (1500 PSI at 300K for a couple of days). In the supergrating (superimposed gratings), the sub-sets were inscribed in the guide one by one, each of which is designed to tap out one wavelength from a common input and direct it to one chosen output (direction). However, the inter-grating couplings can distort the diffraction characteristics of the individual grating sets in the strong coupling regime, as we found several years ago. Therefore, a proper design of supergrating WDM devices must take the inter-grating coupling effects into account. For this reason, we developed a coupled

mode theory, on the basis of which we carried out all device designs. For a first proof-of-concept demonstration, we selected one of the simplest designs: a 1x4 WDM in Ge-doped silica, with outputs of 830nm, 840nm, 850nm, and 860nm at +32, -26, 26, and +32 degrees, respectively. The measured diffraction efficiencies vary from 70% to 30%, whereas the FWHMs are around 3nm and the crosstalks are between 10 to 15 dBs. For a second demonstration, we implemented a 1x8 WDM in LiNbO waveguide with channel spacings of 2nm and 15dB crosstalks. With low but adjustable level of power tapping off ratio (=diffraction efficiency), this WDM tap-off device is able to function as a wavelength selective power splitter for multiple channels in, for instance, cable television or broadcasting applications.

OEIC DESIGN AND MODELING TOOLS

As Optoelectronics changes from a technology dominated by discrete components to one consisting of integrated modules and Optoelectronic Integrated Circuits (OEICs), it is self-evident that modeling tools must keep up, and simulators suitable for both discrete devices and OEICs are needed. For simulating the discrete OE devices, we have developed a self-consistent powerful two-dimensional tool: Finite Element Light Emitter Simulator (FELES), that is capable of simulating the electro-thermal-optical interactions of OE device structures with any number of terminals, materials and doping zones [10-11]. It has been continually improved and extensively used both in our lab and by our industrial partners in design and modeling of 980nm, 1300nm and 1550nm FP and DFB lasers as well as GaAs-based MESFETs, HEMTS and HBTs [12-14]. For the OEICs, we have recently developed a simulator [15] called OE^{UT} – SPICE, that is made compatible to the popular electronics circuit design tool - SPICE. It is developed from first principles and expressed in three coupled lumped-element equivalent sub-circuits: one electrical, one optical with equivalent optical capacitors, optical resistors and optical current sources; and one for thermal conduction and heating with equivalent thermal resistors, thermal capacitors and thermal current sources. OE^{UT} – SPICE has been validated by experiments on discrete laser diodes, laser diode arrays and HBT-Laser modules. Very good agreements have been consistently obtained under varying operating conditions: DC, transient, and different duty cycles [16-18].

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Organizer /Committee	NATO ARWs and ASIs, and Intl. Conferences
Chair,	Canada-US Workshop on "Frontiers in Optoelectronics", 1996.
Principal Investigator	Ontario Laser and Lightwave Research Center (OLLRC)
Principal Investigator	Ontario Center for Material Research (OCMR)
Key Associate	Information Technology Research Center (ITRC)
Consulted for	Bell-Northern Research Ltd., ITS Electronics, Spar Aerospace, COM DEV. Yukohama R&D Labs of Furukawa Electric (Japan)

Honors & Awards:

Steacie Prize of Canada, 1995.
James M. Ham Chair of Optoelectronics, 1992-present
Conference Board of Canada - NSERC Award for "Best Practices in University-Industry R&D" (Honorable mention), 1995.

Supervisor of the Winner of the "Best Student Paper Award", LEOS'94
Supervisor of the winner of a Doctoral Thesis Prize of NSERC (Engineering), 1995.

Publications:

~90 papers in refereed engineering and physics journals
~50 papers in refereed conference proceedings

Invited Talks:

~50 at international meetings, universities and R&D centers in USA, Japan, France, China & Canada.

Patents: 8 issued; 5 more pending.

Research Activities:

Semiconductor quantum electronics and high speed devices (theory & experiment). Currently leads a group of 15 researchers conducting research projects on:
(I) Quantum and optoelectronic devices (980nm & 1550nm power lasers, lateral current injection lasers, WDM filter/router/adder/droppers, analog lasers, HBTs and novel tunneling devices etc.)
(II) Optoelectronic integration (Enabling device technologies, Design&Modeling tools, Integrated laser/amplifier/WDM in doped glasses etc.)
(III) Quantum physics and Materials (QWs & Nanostructures, strained & Strain compensated QWs, interband and e-o couplings, laser instabilities, nanowire arrays, spectra/spatial/temp. resolved profiling of devices.)

Most of these are funded by agencies and corporations of Canada, Japan, France and USA.

Optoelectronic Device Integration for Telecommunication and Sensors Support.

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There are several important advantages to be gained by the monolithic integration of multiple components such as lasers, modulators, switches, detectors and interconnects on the same semiconductor substrate for optoelectronic applications. In particular, compactness, reliability, and power dissipation could be enhanced with these photonic integrated circuits (PICs). However, progress has been slow due to material issues, semiconductor growth technique limitations, overall power dissipation and topology issues when multiple components are used.

During the past three years, our efforts in IMS were mostly directed towards wavelength division multiplexing (WDM) due to its potential for increasing transmission bandwidth and allowing flexible networking options in optical fibre transmission and sensor systems. Several design and fabrication issues have been addressed during our efforts towards building fully monolithic WDM transmitters and receivers. However, the monolithic integration of different devices such as detectors, modulators, sources, as well as the required interconnections for both optical and electrical signals, is only practical if suitable device performance and lifetime can be maintained for the whole PIC. This implies being able to modify the effective semiconductor bandgap as needed for each device while maintaining overall device and material compatibility under control. Indeed, if one could grow each device separately in different areas of the common substrate this would be

easily achieved. This, however, is a considerable challenge from the point of view of material compatibility, growth techniques and manufacturability. Several efforts using techniques such as selective area regrowth and selective area growth to obtain integrated devices on a common substrate resulted in working PIC prototypes but at the cost of increased complexity, many tens of growths and lithographic steps, that resulted in low yield and high manufacturing cost when compared to discrete devices or even hybrid systems. Another method explored in this program was selective area pumping. The advantage here is simplicity resulting from a common set of layers for both InGaAs quantum well lasers and optical interconnects. The interconnect and waveguide regions were electrically pumped to induce transparency. This, unfortunately, also exacerbated on-chip heat management issues and crosstalk between lasers, as well as adding unwanted spontaneous emission noise to the combined output signals.

A new technique, developed by members of the IMS Quantum Physics and Optoelectronics Groups, was thus explored to allow the convenience of a single and common growth step for all devices without the need of electrical pumping to modify material bandgap. After the wafer growth, a high energy ion beam (typically, As^+, 2 to 4 MeV with doses of 5 x 10^{13} to 5 x 10^{15} cm^{-2}) was used to implant though a suitable mask. A rapid thermal anneal at 750C then allowed the ions and defects to diffuse and enhance the quantum wells intermixing at the interfaces. The resultant carrier confinement and electronic levels shift in the broadened quantum wells modified the effective bandgap of the structure locally, as defined by the mask. The mask controlled simultaneously both the penetration depth as well as the effective dose of the ions as a function of the semiconductor material depth. This resulted in spatially different intermixing for different regions to effectively delineate the local bandgap of the device. This technique was also successfully applied to active devices such as lasers, to tune the emitted wavelength over a range of 80nm in wavelength, with negligible effects on device lifetime. This is a very powerful and practical method for device integration in planar geometries that potentially

eliminates the need of multiple regrowths to achieve a spatially variable bandgap for each device function.

At this time photonic integrated devices are at a disadvantage when compared to conventional hybrid circuits in terms of fabrication complexity, material and heat generation issues, demonstrated performance and most importantly manufacturability. No "killer app" has yet been identified for PICs to bring low cost with high volumes when compared with established hybrid integration technologies which is more suited for niche type applications in specialised and medium volume applications. Some interest in telecommunication and free space interconnects (terabit bottleneck and rapid signal processing for example), military and sensor support may allow further development in monolithic integration to enable PICs to become viable in the present context. These directions will be most likely due to improvements in selective area growth and regrowth, bandgap shifting techniques and "monolithic" modelling techniques encompassing optical, electrical and thermal interactions when the PIC is viewed as a system.

Applications of Band Structure Engineering in Optoelectronic Devices for Telecommunication Systems

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Bandwidth requirements for fiber-optic systems have increased approximately by 4 fold every 5 years since the early 1980's. Today, 10 Gb/s systems are ready to be deployed and 2-8 wavelength 10 Gb/s wavelength division-multiplexing systems to increase total transmission capacity to 20-80 Gb/s are under development. Optoelectronic devices to function in such high capacity systems need to deliver stringent wavelength tolerance, wide bandwidth, high efficiency, increased optical power, controlled chirp performance, and superior quality with respect to reliability.

Optoelectronic devices designed on bulk materials have been facing increased difficulties to meet the required system specifications. Low dimensional structures in conjunction with band gap engineering are vital for achieving the needed device performance which could not be provided by bulk materials.

For example, in order to transmit 2.5 Gb/s NRZ optical signal over 100-400 km of non-dispersion shifted single mode fiber at bit error ratio of 10^{-17} or better, low chirp distributed feedback laser with wavelength chirp of 0.3 - 0.1 nm at 27 dB down from peak is essential to overcome the cumulated dispersion of 1600 - 6400 ps/nm. DFB laser with strained-layer multiple quantum well design that utilizing band gap engineering to modify the material gain characteristic is capable in delivering low chirp, high efficiency, and low threshold current.

At 10 Gb/s modulation speed, light source even with zero chirp is not capable to achieve bit error free transmission of optical signal through 100 km of non-dispersion shifted fiber; well controlled amount of chirp is needed. In this case, quantum stark effects have been incorporated into the design of low voltage MQW Mach-Zehnder interferometry modulator to achieve the needed chirp characteristic. Whether this type of modulator would allow 40 Gb/s modulation is currently under studying.

Low dimension and band structure engineering have found the vital role in optoelectronic devices not only by providing new physical properties to enhance device performance. The most important impact might be in creating innovative device technology. Superlattice has now been used to suppress the propagation of dislocations in the design of long-life high power 980 nm pump laser for fiber amplifier application. In the long run, the application of superlattice might lead to the possibility of combination of various materials on a common substrate such that different device technologies could be hetero-integrated.

Challenge remains in applications of low dimension structure and band gap engineering to create new device functionality for the realization of advanced information networks in the 21st century.

As broadband is brought to the end users of information, fiber access needs low cost, highly reliable optoelectronic devices that could be operated in a wide temperature range, and optical date communications would benefit from 1D/2D arrays which could be operating at high speed without bias. At present, progress in this end is mainly due to technology development rather than through band structure engineering. Semiconductor laser operating at 1.3 - 1.5 μm wavelength range still suffer the traditional temperature dependence of threshold current and efficiency. The potentials of lower dimensional quantum wire/dot on optoelectronic devices have not been fully explored, neither are their possibilities on offering new physical properties for new functions such as optical switching, optical logic and memory. Although some progress has been made currently in wavelength conversion by four-wave mixing in quantum well waveguides (which is vital in developing an all optical network by wavelength routing), little has been done on developing squeezed light for low noise RF optoelectronic devices for microwave optical links where the requirement of dynamic range of 150 dB could not be accomplished by present optoelectronic devices.

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Optoelectronic Signal Matrix

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Optoelectronic Switch

In its most general sense, a telephone switch distributes incoming signals in parallel to an orthogonal set of output lines. By means of a set of switches attached to each output line, a given input signal can be selected.The multiple input signals can be viewed as a vector. Each output line is logically an OR function of the inputs (actually multplication of each by either 0 or 1, followed by summation of the results). The operations performed correspond to vector-matrix multiplication.

We have developed an optoelectronic matrix switch for the very broadband (>1 GHz bandwidth) digital signals now routine in telecommunications. It makes use of optical distribution of signals on waveguides to avoid electromagnetic leakage, and employs the photodetection process to perform the switching function, thus avoiding the many problems associated with attempting to switch light itself.

In the prototype, ten incoming electrical signals are converted to optical signals using inexpensive lasers designed for CD players. (These lasers set the bandwidth limit currently experienced.) The resulting optical signals are split ten ways by optical fibre taper couplers, and one fibre from each input is gathered to form a bundle of ten fibre to each output.At each output is an optical receiver which consists of a high gain amplifier fed from an array of controllable photodetectors, one receiving each signal.

The controllable photodetectors are GaAs Metal-Semiconductor-Metal Schottky double diodes.These devices are easy to make, have intrinsically low capacitance and hence high speed, and most important, are in a low sensitivity state when unbiassed. The two Schottky diodes forming each detector are opposed, so that there is no internal field when the detector is unbiassed. When bias on the order of a volt is applied in either direction, a sensitive state, and thus a connection between an input and an output, is established.

The MSM devices corresponding to a single output port share one electrode and the summing function is performed by photocurrent summation. The weight values of the matrix are not restricted to the binary set (0,1) used in switching. MSM diodes can be rendered partially sensitive by biassing them between approximately ±0.5 V. (Photocurrents from crosspoints biassed oppositely will subtract in the bus.) Receiver gain is designed to make up for power splitting and other losses so that the output levels equal the input levels. Thus the matrix elements can take any value between normalised -1 and +1. The bias for each MSM is controlled by a dedicted 10 bit D/A converter .

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Applications

There has been interest in this switch for several applications in modern broadband communications networks. However, its features need to be considered closely.

- It is a fundamentally analogue routing device, much like an optical switch. It performs this switching function with very high quality, comparable to or better than an optical switch, but has a bandwidth limit. (While optical switches do not themselves have bandwidth limits, the terminals they feed do have essentially the same limits as the optoelectronic switch.)

- It performs much better than an electronic matrix in the analogue switching role, but is probably considerably more expensive.
- It imposes an optical to electronic conversion, so that the reverse conversion is required if the signal is to proceed in an optical network. While this is a novel approach, there may be advantages over optical switching. Conversion between optical and electronic signals is inherent in all photonic communication systems. Optoelectronic matrix technology uses this conversion to achieve the broadband switching function in a bandwidth and format transparent manner

Some suggested applications are in protection switching and in wavelength based signal routing.

-Optoelectronic protection switching affords protection against failure of either optical path or optical transmitters and receivers:
-Broadband, transparent electronic switching with passive WDM components and existing transmitters and receivers allows wavelength conversion routing at each switching node

Performance

The residual sensitivity of the crosspoints at zero bias is better than 50 dB below the on- state sensitivity over the entire response bandwith. By tuning the off- state sensitivity a few millivolts to counter residual fields in the device, the switching contrast can be increased to 60 dB.

Crosstalk is not measurable in this switch. For the experiment shown in the figure two sinusoidal signals at different frequencies near 1 GHz were applied to two adjacent input ports. The corresponding crosspoints were turned on so that both signals appeared at one out put port. At an adjacent output port the only crosspoint corresponding to one of the input ports was turned on. There is no sign (to - 60dB) of the other signal at this port.

The 1.25 GHz bandwidth of the switch is set by the lasers. This bandwidth is slightly below the Nyquist criterion for the 2.488 Gb/s signals of the OC-48 standard for telecommunications. Nevertheless we obtain open eyes for OC-48 signals passing through the switch, and bit error rates less than 10^-9

Bypassing the input lasers with a high frequency optical signal we have measured a bandwidth of 2.5 GHz for the matrix.

The paths through the switch have much greater signal to noise ratio than necessary for binary signals. It is possible to employ multilevel signals in which each signal state signifies more than one bit. We have transmitted four level signals carrying two bits per symbol at a symbol rate of 1.8 GHz, and retained quality.

Few available analogue signals challenge the capacity of the switch. We have passed a single signal consisting of 40 frequency division multiplexed channels of NTSC television through it. We have simultaneously carried 2.488 Gb/s on one port and analogoue television on another with no degradation to either.

Optoelectronic Signal Processing

Optoelectronic switching matrices can be used to perform various signal processing functions. Because optical signals are intrinsic to them, the excellent delay properties of optical fibre can be used.

Variable Delay Line: By reconnecting outputs to inputs, multiple passes through an array of delay lines can be arranged, providing for the discrete synthesis of delay according to binary composition.

Array Antenna Control:A single radio frequency or IF signal applied with various delays at the input ports can be distributed to an array of antennas under the control of the matrix. Thus the appropriate delay can be switched in at will. This is a true delay, so that

the array steering is not affected by signal frequency as in a "phased" array. True time delay under the control of an optoelectronic switch has recently been demonstrated.

Discrete Time Filter: By connecting outputs back to inputs through a set of delay lines whose lengths increase by a discrete increment, it is possible to employ the weighted summation function to construct discrete time filters. Simply by appropriate setting of the crosspoints, a single physical device can be reconfigured as any form of filter: finite or infinite impulse response in canonical forms I or II, as well as lattice filters. Both the filter configuration and the filter weight values can be set in real time. Because negative as well as positive weights are possible, filters with lowpass, bandpass and highpass characteristics can be synthesised. WIth the 10x10 switch, FIR and IIR filters of up to 19 taps can be made.

A complication of the use of MSM photodetectors to set the filter tap- weight coefficients is that the bandwidth of the filter taps is coupled to their weight value. Reduced bias increases the carrier transit time, allowing more recombination to occur, and therefore reduces sensitivity. But the maximum frequency the to which the detector responds is decreased. The interaction between sensitivity and bandwidth is complex in practice, and good models are not yet available.

By an iterative method we have designed filters in which the filter response compensates for tap rolloff. The tap response is modelled, and the model used in a simulator of the filter performance. The simulated performance is compared to that of an ideal filter and the difference drives a least squares recalculation of the tap bias settings.

The prototype signal matrix was constructed to contain fibre delay lines with lengths that increment by 1 ns propagation time at each input port. These delay lines are located between each laser and its corresponding power splitter. Reflex connections from output to input are made with short lengths(<10 cm) of semi- rigid coaxial cable.

Comparison of simulated and measured transfer functions of a nine- tap filter shows good agreement up to 500 MHz. Since the free spectral range of a discrete time filter with a tap rate of 1 GHz is 500 MHz, the degraded performace above 500 MHz due to the tap- weight to bandwidth coupling is not significant.

Such a filter might, for example, be used to compensate for distortions in communications systems. As an example we have simulated the equalisation of intermode dispersion is graded index optical fibre. The normal bit rate.distance limit for such fibre is under 1 Gb/s . km. With an optoelectronic equalising filter the reach at 1 Gb/ s is extended to 4 km.

The further development of optoelectronic signal matrices now requires a better way to distribute the light. Optical integrated waveguide, or some form of free space propagation must replace individually -handled fibres. We have therefore established a programme developing integrated optical methods of signal delivery in optoelectronic switch matrices.

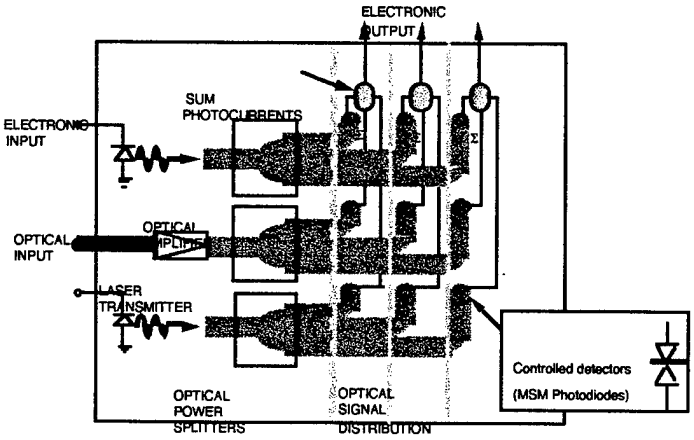
One easily produced type of waveguide is dispensed directly from capillaries mounted on numerically controlled positioners. We have obtained excellent propagation performance in such waveguides, and have found simple methods to extract light from them into surface mounted detectors. Our multimode polymer waveguides show a loss of about 0.1 dB/cm.By cutting the plastic with a numerically controlled blade, angled facets can be produced that reflect the light up or down. We have found it possible to grade these taps in order to give up to five taps in tandem that give equal levels of power extraction within ±1dB.The taps must be several millimeters apart to allow mode redistribution.

Laser written polymer guides are also under investigation. It is possible to make planar power splitting couplers withlow excess loss (.25 dB) this technique.

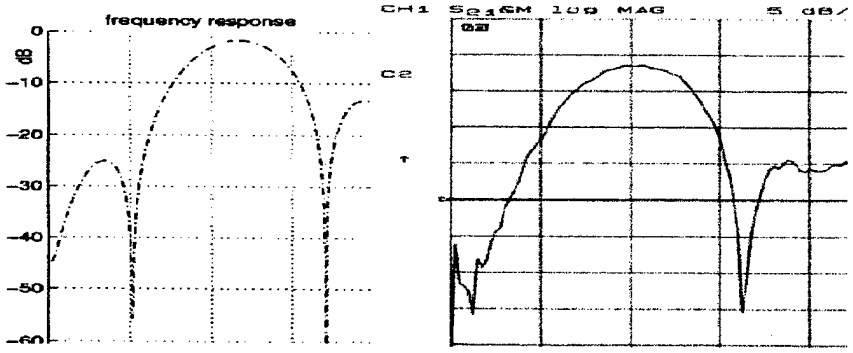
The dispensing method is also used to generate lens arrays of surprising ly high quality and controllability. f- numbers between 1 and 16 can be reliably obtained. Focal length variation in the dispensed lenses is tightly controllable. These lenses are diffraction limited. They are currently generating much interest for a wide variety of applications.

Two new matrix prototypes are now in design. One will use dispensed waveguide power splitters to make a small, convenient switching submodule.The other uses free space distribution of the signal. After collimation by dispensed lenses on one side of a glass substrate a linear array of optical signals are split by a Damann phase grating formed by reactive ion etching on the other side. The msm array is a monolithic two dimensional array on which a spot is incident at every detector. The structure is very convenient to make, but the experimental device suffers from crostalk at about -30dB due to optical scatter. This is likely avoidable.

Figures



Concept of the Optoelectronic Matrix



Filter sythesis over 0-500MHz: 9 taps FIR

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>
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>Churchill Research Rocket Range, Fort Churchill, Man., beginning a career
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> In 1985/86 he was guest scientist at the Heinrich Hertz Institut in
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Confined and Interface Optical and Acoustic Phonons in Quantum Wells and Quantum Wires

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ABSTRACT

As device dimensions in nanoscale structures and mesoscopic devices are reduced, the characteristics and interactions of dimensionally-confined longitudinal-optical (LO) phonons and acoustic phonons deviate substantially from those of bulk semiconductors. This account will emphasize the properties of both LO-phonon and acoustic-phonon modes arising in semiconductor quantum wells and quantum wires. In particular, this talk will highlight recent results of both microscopic and macroscopic models of LO phonons in polar-semiconductor quantum wells and quantum wires with a variety of cross sectional geometries. In addition, the elastic continuum model will be applied to model acoustic phonons in both polar and non-polar semiconductors.

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Present Position:	Senior Research Scientist, U.S. Army Research Office (ARO), at ARO since February 1985.
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	Yale University Fellowship 1970-1972
	1977 Recipient of the Research Initiative Grant of the Director of the Los Alamos Scientific Laboratory
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ELECTRON MICROSCOPY OF QUANTUM DOTS AND NANOPRTICLES

BY

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In the present work we describe the methods to characterize quantum dots and nanoparticles using high resolution electron microscopy and related techniques.

Particular emphasis is made on the case of semiconductor quantum dots embebed on a crystalline support. An exanple of this case is the system AsGa/si. The detaills of the contrast are discussed.

It is concluded the information that can be obtained with a TEM demands theoretical calculationsin order to be reliable.

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1991-94	Deputy Director of The National Council for Science and Technology (CONACYT)
1992-94	Executive Secretary of the National System of Research (México)
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1980	Head of the Condensed Matter Department, Institute of Physics, University of Mexico.
1978	Senior Research Associate, Materials Science Branch, NASA-AMES Research Center, Moffett Field, California, U. S. A.
1977	Full Professor of Materials Science, Department of Solid State Physics, Institute of Physics, National University of Mexico.
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D COMMITTEES AND PROFESSIONAL MEMBERSHIP

- Materials Research Society
- American Vacuum Society
- American Physical Society
- Microscopy Society of America
- Mexican Materials Research Society (Past President)
- Mexican Catalysis Society (Past President)

- Mexican Electron Microscopy Society (President)
- Mexican Academy of Sciences
- Chairman of Mexican IUPAP Committee on Physics
- Member of International Committee of Quasicrystals
- Member of International Committee Strength of Materials
- Member of Latin American Surface Science International Committee
- Member of The International Committee on Nanostructured Materials
- Representative of Mexico in the International Union of Materials Research Societies (IUMRS)
- Member of the Executive Committee of the International Federation of Electron Microscopy Societies (IFSEM)
- Member of the ICSU Committee on Science Capacity Building
- Honorary Member of the Materials Society of India
- Fellow of American Physical Society
- Chairman of the Materials Program of Iberoamerican Scientific Collaboration (CYTED)

E HONORS AND AWARDS AND PRIZES

- Ford Foundation Fellowship (at UNAM)
- National Research Council Fellowship. (At NASA AMES Research Center)
- Guggenheim Fellowship (1988)
- National Prize in Exact Sciences of the Mexican Academy of Sciences. (1982).
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- National Prize of Sciences in Mexico (1992)
- Chairman of the II International Conference on Quasicrystals (1987)
- Chairman of the First International Meeting on Nanostructured Materials (Sept. 1991)
- Chairman of The II Interamerican Congress of Electron Microscopy. Mexico (1992)
- Chairman of the IV International Conference of Advanced Materials ICEM IV (Cancún-México, Sept. 1995)
- Chairman of the 14th International Conference on Electron Microscopy ICEM 14th (Cancún-México, 1998)
- Mexican Representative on the OECD Group on Megascience

F PUBLICATIONS IN THE SCIENTIFIC LITERATURE:

I.	Review Papers and Chapters in Scientific Books	8
II.	Scientific Papers	170
III.	Books	4

Making Nanostructures on the Cheap

Martin Moskovits, Dimitri Routkevitch, Jimmy Chan, Dyiaa AlMawlawi and Jimmy Xu

A method will be described for making arrays of metallic or semiconductor nano-wires or nano-dots of uniform size by means not involving MBE. The technique involves "casting" the desired materials into templates whose wells are of uniform size. The resulting arrays have been used in a number of prototypical device applications including the formation of structures exhibiting coulomb blockade effects and the fabrication of textured surfaces that form excellent targets for x-ray lasers.

Biography.

Martin Moskovits was educated at the University of Toronto where he is now Professor of Chemistry and Chair. He has been a member of the Ontario Laser and Lightwave research Centre, an Ontario Centre of Excellence and of CEMAID, a federal Network of Centres. His research interests include the optical and electronic properties of materials, clusters and nanostructures.

Using Quantum Interference to Control Semiconductor Photocurrents

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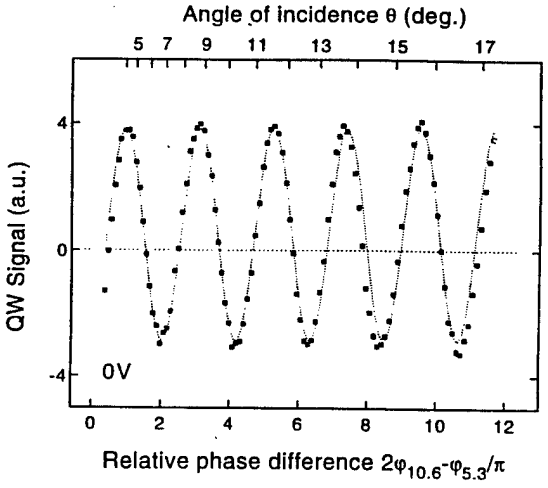
Abstract: Using the superposition of fundamental (ω_1) and second harmonic (ω_2) light, we experimentally demonstrate that both the magnitude and the direction of a photocurrent in a quantum well device can be controlled.

Modern semiconductor physics shares many phenomena with atomic and molecular physics. Quantum wells are somewhat like atoms. Multiple quantum wells are similar to molecules. We describe an experiment [1] that is the semiconductor analogue of a recent atomic physics experiment [2].

Using the superposition of fundamental (ω_1) and second harmonic (ω_2) light, both the magnitude and the direction of a photocurrent is determined by the relative phase of the beams in an unbiased quantum well device. To do this, an electron is produced in the continuum either by means of a single photon transition producing an asymmetric continuum wave function at ω_2. If the coherent superposition of these electron wave functions destructively interferes in one direction, they must constructively interfere in the other, implying a current flow in that direction. The relative phase of the light determines the relative phase of the electron wave functions and therefore, their direction.

To perform this experiment, a 25 well GaAs/ $Al_{0.26}Ga_{0.74}As$ device was used with well width of 55 Å and well separation of 325 Å. The separation between the first two sub-bands (152 meV) was far detuned from the photon energy of the 10.6 μm fundamental photon. Electrons were δ-doped into the wells in such a manner as to ensure that the device showed no photovoltaic response when unbiased.



The 10.6 μm output of a TEA-CO_2 laser, together with its second harmonic produced in a $AgGaSe_2$ crystal, was used as a phased optical sources. The relative phase between the 10.6 μm and 5.3 μm radiation was controlled by varying the tilt angle of a 1 inch thick NaCl crystal through which both beams passed.

Figure 1 shows the output from the quantum well device plotted as a function of the difference in the phase difference of the 10.6

μm and 5.3 μm radiation. The output was measured by detecting the current passing through a 50 Ω resistor with a box car integrator. The current flows in either direction in the device depending on the relative phase of the 10.6 μm and 5.3 μm radiation.

These experiments point to a method of studying such fundamental semiconductor properties as electron dephasing as well as such practical applications as high speed switching without the inductive and physical limitations of wires.

The control over the direction of photocurrents that we demonstrate is simply the electronic analogue of the control over the direction of light that is achieved in an interferometer. As such it is recognized as a general property of the wave nature of matter. Its possible application to chemistry is very important [3].

Although it is often noted that atomic, molecular and solid state physics are strongly entwined, it is rarely used. We conclude with one other examples: Researchers have recently predicted the destruction of tunnelling in intense, time-dependent fields in double quantum well structures[4]. Double well potentials also occur in diatomic molecular ions. In molecular ions, the destruction of tunnelling is responsible for two new effects. (1) A new ionization mechanism leading to many orders of magnitude in the ionization rate when the internuclear separation of the atomic fragments in the region where electron tunnelling is destroyed[5]. (2) The kinetic energy of fragments that is observed in photodissociation of molecular ions is intimately related to the destruction of tunnelling [6] first discovered by semiconductor physicists.

The new understanding that is emerging from molecular theory and experiment point to new approaches to the control of semiconductor photocurrents multiple quantum well semiconductor devices.

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Ultrafast Optical Phenomena in Low-Temperature-Grown GaAs

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CANADA

Over the last few years, we have shown that low-temperature MBE-grown GaAs exhibits some remarkable nonlinear optical properties [1,2]. In particular, under suitable conditions, large and rapidly-responding optically-induced refractive index changes have been observed.

An example of the dependence of the index change in as-grown GaAs:As on the intensity of 3ps laser pulses is shown in Fig. 1 for a series of wavelengths that span the band edge of GaAs:As. Index changes approaching -0.1 are observed for laser pulses at 870nm which is above the bandgap of the material. These changes are 2-3 times larger than those observed for normal high-temperature-grown GaAs [3]. The measured index changes are of the opposite sign from those caused by thermal effects.

We have developed a simple phenomenological rate equation formalism to model the observed index and absorption saturation in low-temperature MBE-grown GaAs. This formalism takes into account the dominant role that traps play in the carrier dynamics. The key processes are shown in Fig. 2. Light resonant with the bandgap will excite electrons to the bottom of the conduction band (N). Our model assumes that excited carriers can be rapidly trapped in mid-gap states (N_T) which are present due to the excess As in this material. These mid-gap states, which have been ascribed to EL2-like defects, can occur with concentrations as high as several times $10^{20}/cm^3$ [4]. Carriers trapped in these mid-gap states can be excited by the incident light to levels high in the conduction band (n). This process gives rise to an additional absorption mechanism in low-temperature-grown GaAs, and can produce a substantially larger carrier concentrations in the conduction band than is possible with just band-to-band absorption. This leads to a larger saturated index change than that obtainable with regular GaAs [1,2,5].

Our rate-equation model has been fitted to the experimental data in Fig. 1, assuming that a steady state population distribution is reached during the 3ps pump pulse. Relatively good agreement with the experimental measurements was found, as shown by the solid lines in Fig. 2. It should be noted that with literature values for the GaAs band-to-band saturation carrier densities, our model predicts the absolute values of both axes for the plotted curves. There are no additional adjustable parameters.

These initial studies were done with pulses of the order of, or longer than, the key relaxation rates. Thus the detailed ultrafast dynamics were not revealed. In more recent work, we performed studies of ultrafast low-temperature MBE-grown GaAs dynamics with a resolution of 150fs. These studies allowed us for the first time to estimate the trap emptying time in this material. This parameter is of crucial importance for ultrafast photonic device applications.

Experiments were performed using 150fs pulses from a mode-locked Ti-Sapphire laser tunable around the band edge of the sample material. The absorption was probed with a variable delay after an intense saturating pulse. Figure 3 shows our experimental pump-probe measurements at $\lambda = 870$nm of absorption dynamics for two samples of low-temperature-grown GaAs with different growth conditions. In each case, the solid line shows a fit of our rate equation model to the experimental data. These samples were chosen to illustrate the absorption dynamics for the cases $\tau_1 > \tau_2$ (Fig. 3a), and $\tau_1 < \tau_2$ (Fig. 3b). For each sample, initial experiments with a relatively weak saturating pulse provided a direct measure of the trapping time, τ_1. Using our measured values for the two-photon absorption coefficient and the trap related absorption in these samples, and taking the same value of the saturation carrier density that was used in the earlier rate equation fits, the rate equations were fitted to the experimental measurements of absorption dynamics with τ_2, τ_3, and τ_4 as fitting parameters.

Table I

a) 3ps experiments	b) 150fs experiments
$\tau_1 = 1.4$ps	$\tau_1 = 1.4$ps
$\tau_2 = 2.8$ps	$\tau_2 = 3.0$ps
$\tau_3 = \infty$ $(>>\tau_4)$	$\tau_3 = 100$ps
$\tau_4 = 0.31$ps	$\tau_4 = 0.31$ps

Table I compares, for the 300°C-grown sample, the time constants found from the rate equation fits for the 150fs data with the quasi-CW (3 ps) data fits reported in [2]. It can be seen that very good agreement is obtained, even though for the 150fs case two-photon absorption effects play an important role, and no assumptions of steady-state carrier concentrations under optical excitation are made. This gives us confidence in the validity of our model, and in the accuracy of the decay times found from the fits to the experimental data.

How can this model be used to aid us in the design of a picosecond optical switch? We will consider a generic waveguide device configuration in which an optically-induced 2π phase shift is required for switching to occur. Using our model, we have investigated the dynamic behaviour of the various absorption mechanisms in low-temperature-grown GaAs, in order to determine the optimum conditions for operation of this type of optical switch. Figure 4 shows the behaviour of the various pertinent absorption mechanisms for a 2.2ps incident pulse assuming a material with parameters as found for the 300°C-grown GaAs material, but with $\tau_1 = 10$ps. It should be possible to adjust material growth and annealing conditions in order to achieve this carrier trapping time. From Fig. 4 we see that the total absorption near the pulse maximum is only ~ 65cm^{-1}. This absorption saturation occurs for a peak power of ~120W -- assuming an optical cross-sectional area of 10^{-7}cm^2 in the waveguide. The maximum waveguide length is limited by the absorption length to ~ 150μm. By "diluting" the active material with another material that is lattice matched but has the band edge far from the operating wavelength, this maximum device length can be substantially increased.

Various figures of merit have been introduced in order to characterize and compare

nonlinear optical materials. In the cases where either one- or two-photon absorption processes determine the absorption length, a figure of merit can be defined by [6]

$$\text{figure of merit} = \Delta n / \alpha_t \lambda$$

where Δn is the light-induced index change, α_t is the total (saturated) one- and two-photon absorption, and λ is the wavelength of the incident light. A figure of merit greater than 1 is required for effective operation of most types of switching devices. For the case illustrated in Fig. 4, we estimate the figure of merit to be ~ 4.4.

Another figure of merit, F, is used to indicate the relative importance of fast, light-induced nonlinear effects and slow thermal heating effects[7]. We estimate that under suitable conditions, F for low-temperature-grown GaAs can be as high as 1000 -- indicating that roughly 1000 switching operations can be performed in a thermal lifetime.

In conclusion, we have shown that low-temperature-grown GaAs can have a large optical nonlinearity and an ultrafast response. We have developed a simple formalism to model this material and have used it to outline the design of an ultrafast photonic switch with good figures of merit. This demonstrates the potential of GaAs grown at low temperatures for ultrafast photonics applications.

We would like to acknowledge the assistance of J. Harbison and his colleagues at Bellcore, and D. Thompson and his colleagues at McMaster University, for providing the samples used for these experiments; and S. Dzioba at Bell Northern Research Inc., for AR coating these samples. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada, and the Ontario Laser and Lightwave Research Centre.

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Figure Captions

Fig 1 Average index changes as a function of average light intensity in a 300°C-grown sample of lightly-annealed low-temperature-grown GaAs during the passage of 3ps pulses at a series of wavelengths that span the band edge of the material.

Fig 2 Band diagram of low-temperature MBE-grown GaAs showing the key excitation and decay processes in the rate equation model. α is the band-to-band absorption coefficient, and α_T is the absorption coefficient due to carriers in the mid-band states. TPA refers to two-photon absorption.

Fig 3 Absorption dynamics for (a) 250°C-grown and (b) 300°C-grown samples of lightly-annealed GaAs after excitation by an intense 150fs pulse at 870nm. For (a), $\tau_1 > \tau_2$; for (b), $\tau_1 < \tau_2$ (see text). The solid line is the dynamic behaviour predicted by our rate-equation model.

Fig 4 Calculated dynamic contributions to absorption for single photon band-to-band, traps-to-band; and two photon (TPA) band-to-band processes for a sample of low-temperature-grown GaAs during excitation by a 2.2ps pulse at 880nm. The trapping time is assumed to be τ_1 = 10ps.

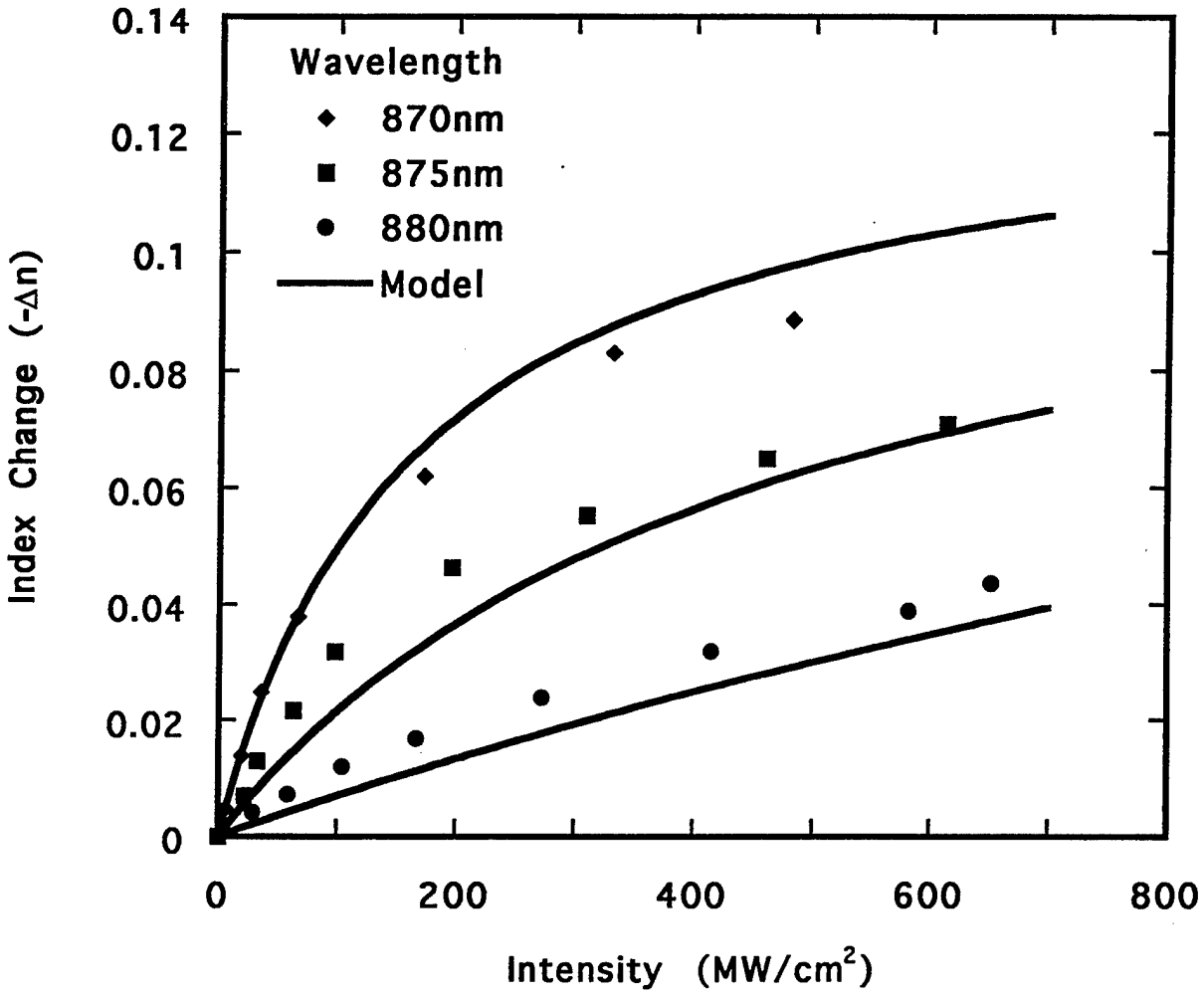
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Index Change (-Δn)
Wavelength
870nm
875nm
880nm
Model
0
200
400
600
800
Intensity (MW/cm²)

Fig.1

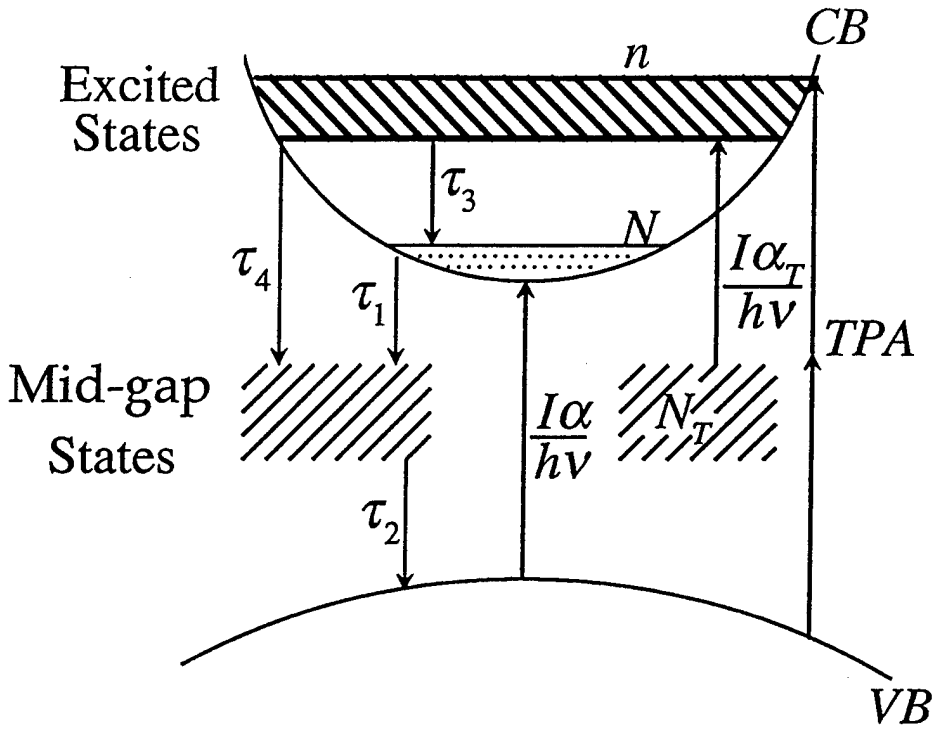
CB
n
Excited
States
τ_3
N
τ_4
τ_1
$\frac{I\alpha_T}{h\nu}$
TPA
Mid-gap
States
$\frac{I\alpha}{h\nu}$
N_T
τ_2
VB

Fig 2

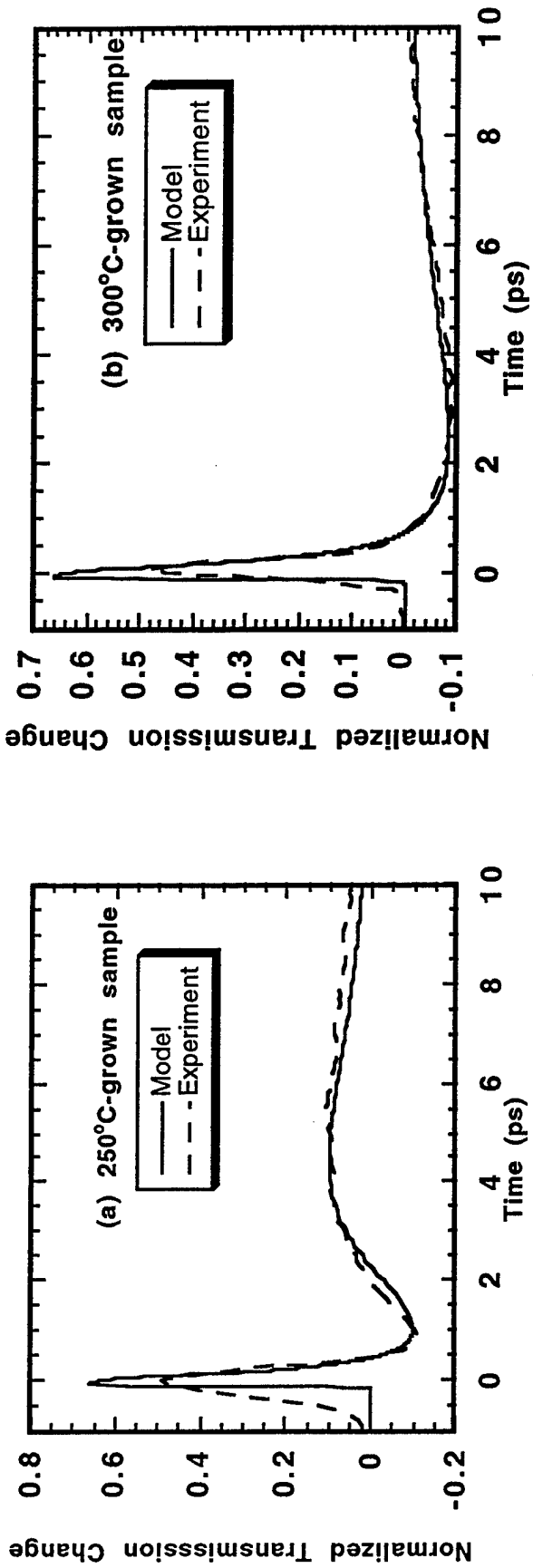
(b) 300°C-grown sample
Model
Experiment
Normalized Transmission Change
Time (ps)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
2
4
6
8
10
(a) 250°C-grown sample
Model
Experiment
Normalized Transmisssion Change
Time (ps)
0.8
0.6
0.4
0.2
0
-0.2

Fig 3

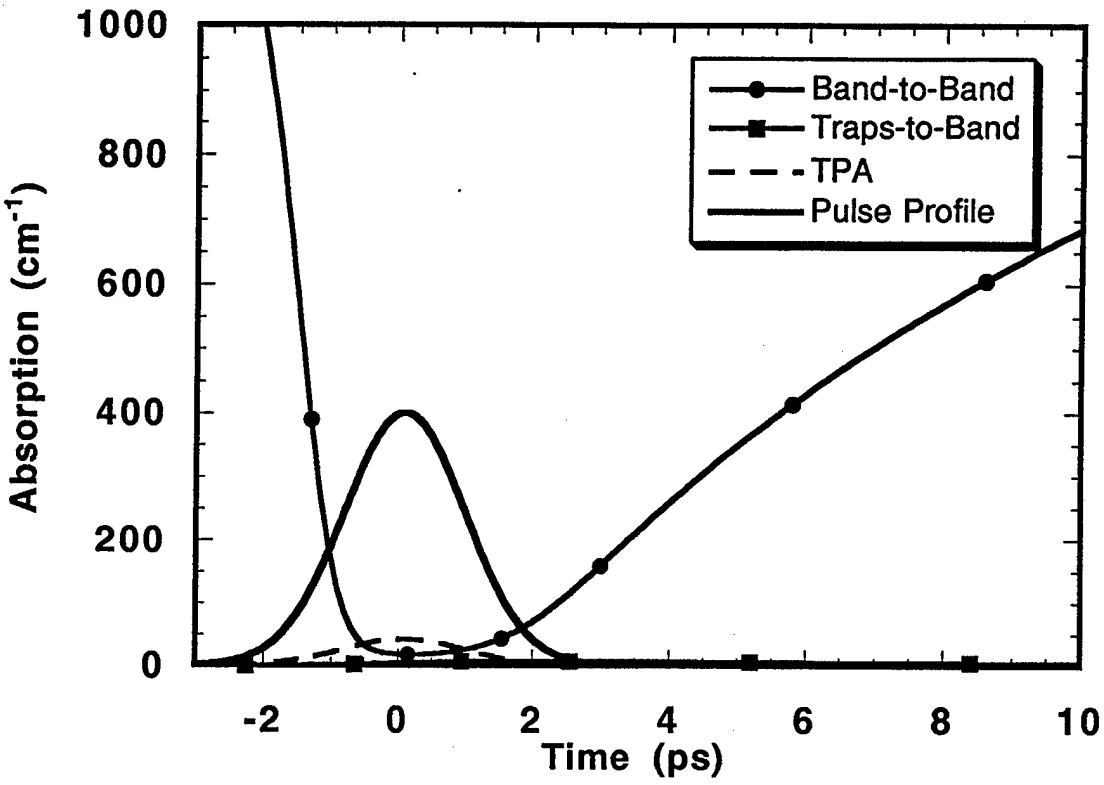
1000
800
600
400
200
0
Absorption (cm-1)
-2
0
2
4
6
8
10
Time (ps)
Band-to-Band
Traps-to-Band
TPA
Pulse Profile

Fig 4

Peter W.E. Smith: Short Biography

Peter W.E. Smith was born in London on November 3, 1937. He received the B.Sc. degree in Mathematics and Physics in 1958 and the M.Sc. and Ph.D. degrees in Physics in 1961 and 1964, all from McGill University, Montreal, P.Q., Canada. His thesis work was on the paramagnetic relaxation of iron group ions in dilute single crystals.

From 1958 to 1959 he was an Engineer at the Canadian Marconi Company, Montreal, Canada, where he worked on transistor circuitry. After obtaining his Ph.D. degree, he joined the Bell Telephone Laboratories in Holmdel, NJ, USA, where he conducted research on laser mode selection and mode-locking, pioneered the development of waveguide gas lasers, and demonstrated and developed hybrid bistable optical devices. In 1970, he spent nine months at the University of California, Berkeley, as Visiting Mackay Lecturer in the Department of Electrical Engineering, and in 1978-1979 he was a visiting research scientist at the Laboratoire d'Optique Quantique, Ecole Polytechnique, Palaiseau, France. From 1984 to 1992 he was with Bell Communications Research, Red Bank, NJ, USA, where for the last three years he was Division Manager of Photonic Science and Technology Research. In July 1992 he became Professor of Electrical and Computer Engineering, at the University of Toronto, Toronto, Ontario, Canada. From 1992 - 1995 he also served as Executive Director of the Ontario Laser and Lightwave Research Centre. His current research interests involve ultrafast optical switching and photonics.

Dr. Smith is a fellow of the IEEE, a fellow of the Optical Society of America, and a member of the American Physical Society, and the Canadian Association of Physicists. He has published over 150 technical papers and holds 32 patents. He has participated in numerous conference organizing committees and has been guest editor for several special journal issues. He served as associate editor of the IEEE Journal of Quantum Electronics from 1976-1979; associate editor of Optics Letters from 1980 to 1982; and editor of Optics Letters from 1991-1995. From 1987 to 1991, he served as editor-in-chief of the IEEE Press book series "Progress in Lasers and Electro-Optics". He is currently a member of the International Advisory Board of the Journal of Modern Optics, and Chair of the Board of Editors of the Optical Society of America. He was the founder of the Photonic Switching Conference and served as co- Chair of the first two conferences in 1987 and 1989. He served as president of the IEEE Lasers and Electro-Optics Society in 1984, and is currently a member of the Board of Directors of the Optical Society of America. In 1986, he was awarded the IEEE Quantum Electronics Award.

The use of AlGaAs in all-optical communication

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Abstract: We will review recent advances in the field of all-optical switching, in particular using the semiconductor AlGaAs. This material has been shown to be an efficient nonlinear material when operated either in the half band gap spectral region, or close to the fundamental absorption edge. We will discuss our work on the compensation both linear and nonlinear chirp using the negative n_2 coefficient close to the band gap. Finally, we will show that by using material disordering techniques it is possible to create areas with different nonlinearities and discuss the potential applications of this technique.

Introduction: As the current demand for higher capacity communications increases, there is a continuing search for faster and more efficient components to increase the usable band width of existing networks. Recent proposals for the use of time division multiplexing and wavelength division multiplexing promise the realisation of terahertz transmission systems. An alternative mechanism, which is receiving an increasing amount of attention, is the use of ultrafast nonlinear optics as a method for producing all-optical networks. The material of choice here has been the silica fiber, which has the advantage of having a very low propagation loss, allowing for long lengths to be used in a single span. However, the nonlinearity of silica is relatively low, making it less efficient when used in short path length integrated devices. There are several potential advantages of moving towards integrated format, in particular, the devices are compact and immune to environmental effects such as temperature and pressure variations.

Over the last five years, much attention has focused on the use of semiconductors for realizing such integrated, all-optical devices. In particular, AlGaAs, operated in the half band gap spectral region, has been shown to have an almost ideal Kerr nonlinearity. A Kerr medium is a material with a nonlinearity that depends only on the instantaneous intensity. The magnitude of the nonlinear refractive coefficient, n_2, in AlGaAs at half the band gap, is around 500 times that of silica. In addition, the mature fabrication technology available allows low loss waveguides and complex device structures to be fabricated. In Figure 1, we show the theoretical wavelength dependence for $Al_{0.18}Ga_{0.82}As$ (band gap 1.65 eV or λg=0.75 μm) of the nonlinear refraction index n_2 and of the nonlinear absorption, known as two photon absorption α_2[1]. The composition $Al_{0.18}Ga_{0.82}As$ was

chosen so that half the band gap occurs at 1500 nm, and that there will be little linear absorption and no two-photon absorption in the second optical communication window[2].

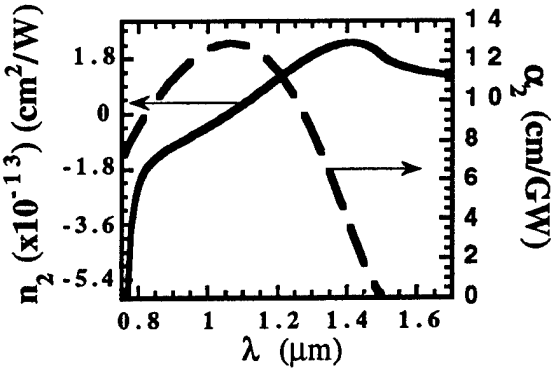

Figure 1: Wavelength dependence of n_2 and α_2 for $Al_{0.18}Ga_{0.82}As$.

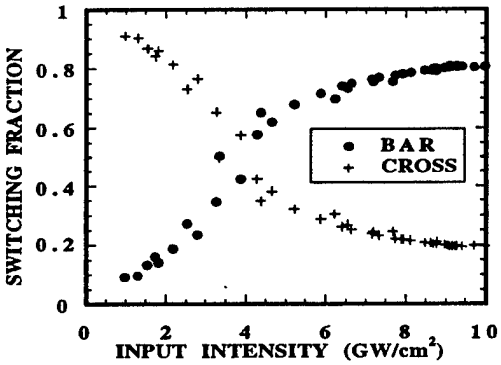

Figure 2: Self switching in an AlGaAs NLDC at 1550 nm.

All-optical switching: Recent experiments have demonstrated all-optical switching in nonlinear directional couplers (NLDC), Mach-Zehnders and X-junctions[3]. In Figure 2, we show the self-switching in a NLDC for 4 psec pulses at 1550 nm. A typical guiding structure consists of a 1 μm layer of $Al_{0.18}Ga_{0.82}As$, between two layers of $Al_{0.24}Ga_{0.76}As$. For a NLDC, the two waveguides are typically separated by 5 to 7 μm, and the device length is 2 to 3 cm. Lateral confinement was achieved by etching part of the cladding to produce 4 to 6 μm wide waveguides using standard photolithographic processes. The switching power in this case is 40W, and with 700 fsec pulses we demonstrated 28 pJ of switching energy[4]. Even without antireflection coating on the facets, we were able to achieve up to 30% transmission, which allowed us to put two NLDC in series on a single chip, showing that integration is possible[4]. To be of practical use, we needed to show that time-division demultiplexing (TDM) is feasible. In a TDM device, a control pulse (possibly from a local clock) should be capable of switching a single signal pulse from a data stream. We have implemented two such TDM devices using a NLDC as the switching element. In the first one, we used different polarizations for the control and signal pulses, while in the second we used different wavelengths[5]. The material has also been used to demonstrate both temporal and spatial soliton propagation.

Chirp management with semiconductor waveguides: There are two spectral regions in which the figure of merit for nonlinear optics is satisfied in semiconductors: one at half the band gap, the other near the band gap. The second one is less attractive because of the presence of both linear and nonlinear absorption. The proximity of the band gap also means that both the chromatic dispersion (β_2) and the n_2 (see Figure 1) are quite large. This is a general trend in semiconductors, not only in AlGaAs. In a similar way to silica optical fibers, the product $\beta_2 n_2$ is negative, meaning that bright optical solitary waves can be propagated in the material. These nonlinear pulses arise from a balance between the self-phase modulation induced by the pulse and the natural tendency for the pulse to disperse. This effect is shown in Figure 3, where the pulse (autocorrelation) width is decreasing as the input intensity is increased[6]. It is remarkable that soliton like behaviour can exist even in the presence of linear and two photon absorption as shown by the saturation of the transmitted power in Figure 3.

The management of the linear chirp produced by chromatic dispersion, and of the nonlinear chirp generated by self-phase modulation, are now becoming the limiting factors in long distance optical communication systems. We have recently shown that the use of a material with β_2 and n_2 of opposite signs than those found in optical fibers, is a way to compensate for the effects resulting from pulse propagation in an optical fiber[7]. We have also shown that this novel approach could reduce the interaction between solitons, and also

reduce the effect of third order nonlinearities in analog transmissions, leading to a possible increase in the bit rates.

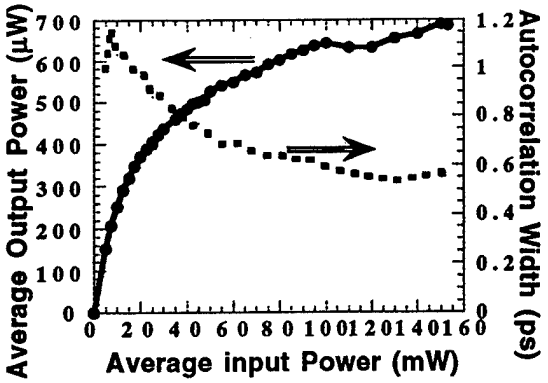

Figure 3: The decrease in the autocorrelation width as a function of the input power. The saturation in the average output power indicates the presence of two-photon absorption.

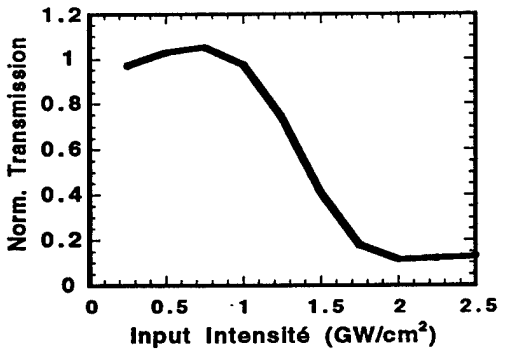

Figure 4: Limiting devices based on the emission of a spatial soliton from a nonlinear waveguide.

Novel devices: If all-optical switching is to be implemented, there is a need to reproduce some of the functions of digital electronics such as thresholding. We have investigated the implementation of such a device by using some recent research that showed that modification of the magnitude of n_2 can be modified by as much as 60%[8]. We have made use of this in the design of a device which would emit a spatial soliton above a certain critical intensity. This emission will reduce the transmission of the waveguide as shown in Figure 4.

Conclusion: We have shown many possible applications for optical communication of AlGaAs both at half the band gap and near the band gap. AlGaAs is a material of choice to study and implement nonlinear planar optical devices since its linear, and nonlinear optical properties, as well as its fabrication technique, are now well known.

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Ultrafast processes in semiconductor doped glasses

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Abstract

We review studies of resonant and nonresonant ultrafast optical processes in semiconductor doped glasses, made at the University of Campinas. First we discuss measurements done in CdTe quantum-dots in glass, excited resonantly. In this case we observe a fast recombination, that depends on the size of the quantum-dot. For the smallest dots, with 3.2 nm average radius, the recovery time constant was found to be 360 fs. Then we describe the observation of the Optical Stark shift in CdS_xSe_{1-x} semiconductor-doped glass (SDG) excited under nonresonant below gap condition and probed with femtosecond optical pulses. An ultrafast and *pure* light-induced shift of the band edge is observed. For a pump intensity of 3 GW/cm^2 the band shifts by 11 meV. The response of the shift tracks the profile of the pumping pulse.

Optical nonlinearities in semiconductor doped glasses (SDG) have been a subject of increasing interest during the past few years due to the fact that they were shown to feature basic requirements for applications in the field of optical information processing. SDG not only exhibit large optical nonlinearities when excited close to the fundamental absorption edge, but also have fast response times. In this paper we review studies of ultrafast proceses in semiconductor doped glasses, both under resonant and non-resonant excitation, done at the Physics Institute at the University of Campinas in Brazil. We have studied quantum-dots of CdTe in a glass matrix, fabricated in our laboratory, and we have also studied commercially available SDG. For the CdTe quantum-dots, we have modeled in detail the confined level structure, we have measured the position of the optical transitions using the photoluminescence excitation technique (PLE) and we have used femtosecond pulses to measure the recovery time for resonant excitation. This recovery time can be as fast as 360 fs. Using a comercially available semiconductor doped glass (Corning Glass CS 2-62)

excited below resonance we obtained femtosecond differential transmission spectroscopy data that show the occurrence of the Optical Stark effect. Monitoring the absorption edge, from 580 nm to 680 nm, during the excitation by a short pulse below the bandgap, we identify a clear rigid shift of the edge away from the pump wavelength, towards higher energies, a clear signature of the Optical Stark effect. The shift of the bandedge tracks almost exactly the time profile of the 60 fs pump pulse and the dependence of the shift with the peak pump intensity agrees well with the Optical Stark effect model.

1. Ultrafast recovery in CdTe quantum-dots in glass

CdTe quantum dots in glass were fabricated by melting a glass host containing SiO_2, $B2O_3$, Na_2O and ZnO mixed with CdO and metallic Te [1]. The semiconductor quantum-dots are produced by a subsequent heat treatment. For the samples studied here, we used an annealing temperature of 580 C for a for a time from 25 to 170 minutes.

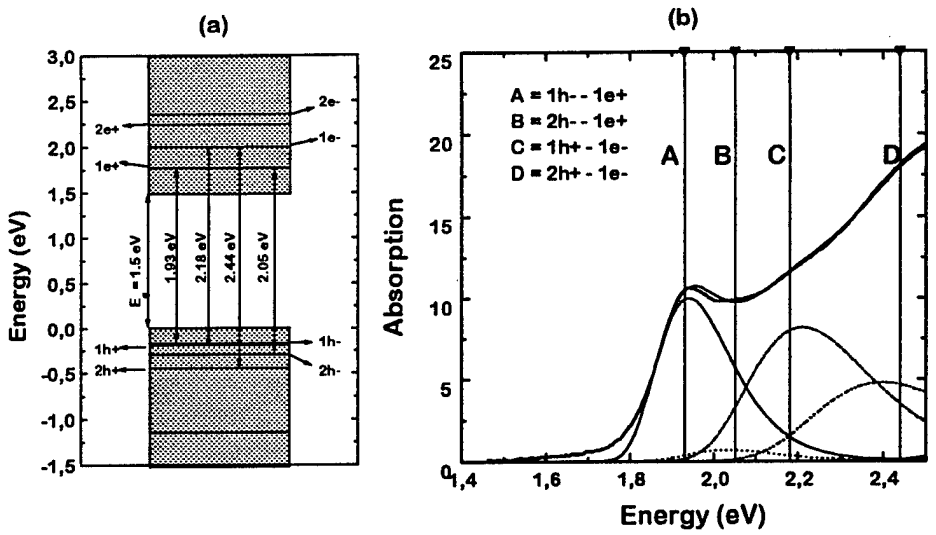

Figure 1. (a) Calculated confined energy levels and lowest lying allowed optical transitions and (b) measured absorption spectrum for CdTe quantum-dots of radius 3.6 nm in glass (annealing time: 25 minutes at 580 C).

Figure 1 shows the optical absorption profile and confined level structure for a sample annealed for 25 minutes. The position of the confined energy levels, and the energy of the allowed optical transitions were obtained using a k.p hamiltonian, including the spin-orbit interaction [2]. In Figure 1, the calculated position for each optical transition is denoted by capital letters A, B, C and D. The ammount of line broadening, which is mostly due to size dispersion of the dots, was found by fitting the measured absorption curve. The best value for the broadening was obtained for a size dispersion of 10% of the average dot radius, for this

sample. Photoluminescence excitation measurements confirm the position of the optical transitions [2]. The data from PLE measurements, together with the calculated position of the optical transitions is shown in Figure 2, showing the excellent match between the model and measurement. As expected, the energy of the optical transitions scales with the inverse of the square of the dot radius.

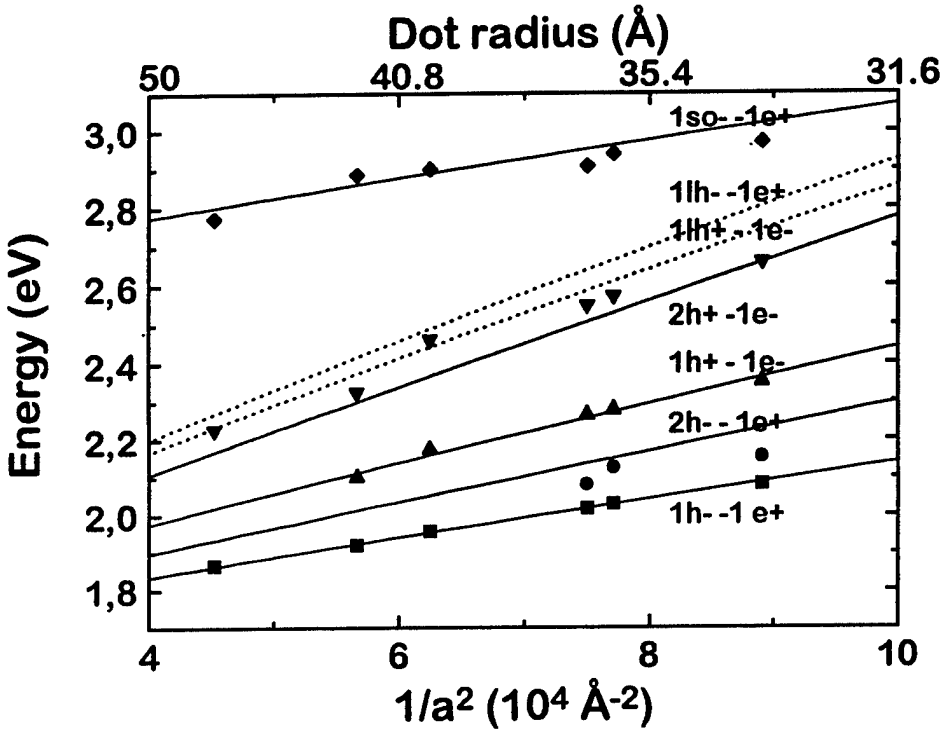

Figure 2. Calculated and measured positions for the optical transitions in CdTe quantum dots in glass, as a function of the dot radius.

The experiment was done using a cavity-dumped colliding pulse mode locked dye laser, emitting 50 fs pulses at 625 nm (1.95 eV) and using the standard pump-and-probe technique. The repetition rate was chosen at 100 kHz, to avoid build-up effects due to eventual slow recovery processes. Figure 3 shows the bleaching recovery traces for the three samples studied. The average dot radius were 3.1 nm, 4.0 nm and 4.6 nm, respectively for the samples with heat treatment times of 25, 95 and 170 minutes.

For the case of the smallest dots (3.1 nm) the bleaching decays with a single time constant of 360 fs, and the recovery is complete. This last feature can be seen from the upper trace in Figure 4, which shows the bleaching recovery in a longer time scale. For the other two samples, we also observe a full recovery, but there are two distinct time constants. For the samples tretated for 95 minutes (average dot radius 4.0 nm) there is a fast initial relaxation with a time constant of 90 fs, followed by a much slower recovery with a time constant of 12 ps. For the samples with the largest dots (tretament time 170 min, average radius 4.6 nm) the initial fast decay has again a time constant of 90 fs, but the final recovery proceeds with a 23 ps time constant.

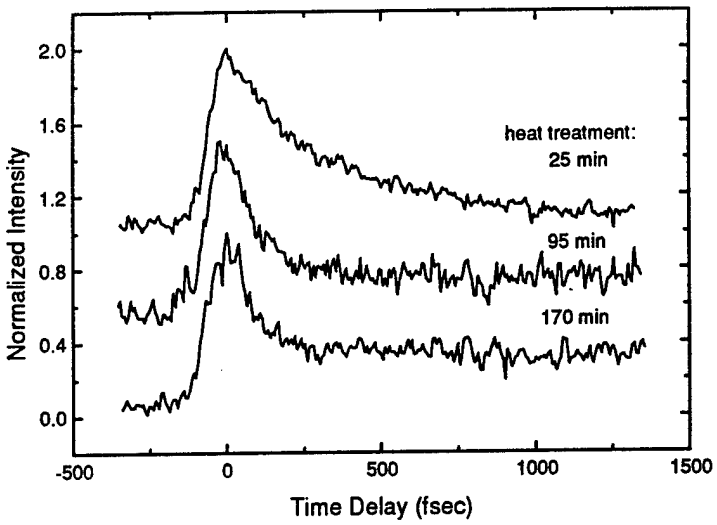

Figure 3. Bleaching recovery traces for three samples of CdTe quantum-dots in glass.

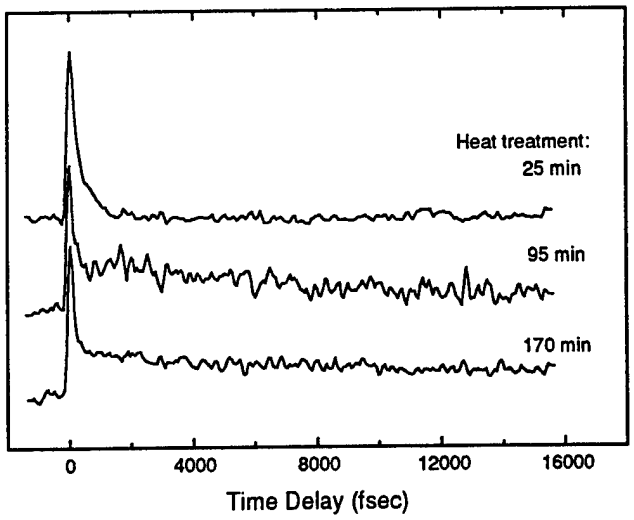

Figure 4. Bleaching recovery for the three CdTe quantum dots in glass samples, shown in a longer time scale than Figure 3.

For the sample with the smallest dots, the excitation is resonant with the lowest lying optical transition, which is the 1h- - 1e+ (transition A in Figure 1b), at 1.93 eV. In this case the recombination and recovery must happen through traps and impurity levels, but there is no intraband relaxation to be expected. For the other two samples (average dot radius 4.0 nm and 4.6 nm), the excitation couples to the transitions A, B and C shown in Figure 1b, due to the inhomogeneous broadening of the transitions. In this case, the levels 1h-, 1h+ and 2h- of the valence band and the levels 1e+ and 1e- of the conduction band are populated. This

prompts an initial fast process, in which intraband relaxation will occur, and this gives rise to the initial 90 fs time constant observed for these two samples. However the final step of the recovery displays a behavior that is clerly size dependent, slowing down from a 360 fs time constant for 3.1 nm dots to a 23 ps time constant for the 4.6 nm dots. We believe that tis behavior is related to the density of traps and impurity states. For the smallest dots, surface effects must speed up the recombination. In fact, for a 3.1 nm dot, more than 55% of the atoms are in the surface, while for a 4.6 nm dot less than 15% of the atoms are surface atoms.

2. Optical Stark effect in a semiconductor doped glass [3]

The sample studied was the SDG CS-2.62 from Corning Glass with a thickness of 500 μm. Measurements were performed using the pump-probe technique. The sample was pumped by 60 fs duration pulses of 7 nm FWHM width, centered at 626 nm (1.98 eV) and with an energy of 350 nJ and the response of the dynamical processes in the system were probed by 12 fs duration probe pulses. The detuning between the central wavelength of the pump and the band gap is 110 meV. The pump and probe pulses were obtained from a colliding-pulse mode-locked laser which pulses, after being amplified in a copper-vapor laser pumped dye amplifier, were split in two beams. Pulses from one of the beams are used to excite the sample. The other beam is sent through a short piece of optical fiber where it undergoes spectral broadening and is compressed with a grating pair becoming the 12 fs probe pulse. The pump and probe polarizations are orthogonal and the probe energy is 1/150 of that in the pump. The transmittance of the probe through the excited sample is monitored by an optical multichannel analyzer. Differential transmittance spectra are recorded as a function of the time delay between the pump and probe beams. The change in the sample transmission is measured by the difference in the transmission of the weak probe pulse with and without the presence of the pump pulse. The differential transmission spectrum is given by $DTS(\omega)=[T(\omega) - T_0(\omega)]\cdot[T_0(\omega)]^{-1} = exp(-\Delta\alpha L) - 1$, where L is the sample length, $T(\omega)$ and $T_0(\omega)$ are the probe transmission in the presence and absence of the pump, respectively. $\Delta\alpha$ is the difference between the absorption coefficient when the pump is present and when it is not.

Figure 5 shows the experimental absorption change, $-\Delta\alpha$, for the CdS_xSe_{1-x} glass CS-2.62 at 300 K for different relative time delays between the pump and probe pulses. Negative time delays indicate situations in which the probe peak precedes the peak of the pump pulse. In Figure 5 we also plot, in the upper trace, the linear absorption and the pump and probe spectra from which we can see that the sample is being excited far below its band gap. It can be seen that for large negative delays the spectra are unchanged from the linear absorption until overlap between the two pulses starts to occur. The curves from Figure 5 show that there is a dynamical increase in the sample transmission. When the measured absorption change for each delay is subtracted from the linear absorption spectrum one can observe that the resulting absorption edge is quickly shifted to the blue as the pump travels through the medium, reaching a maximum at zero delay and then returning almost to the non

perturbed position. For positive delays, changes in the spectra are still observable until 500 fs, which was the largest delay investigated.

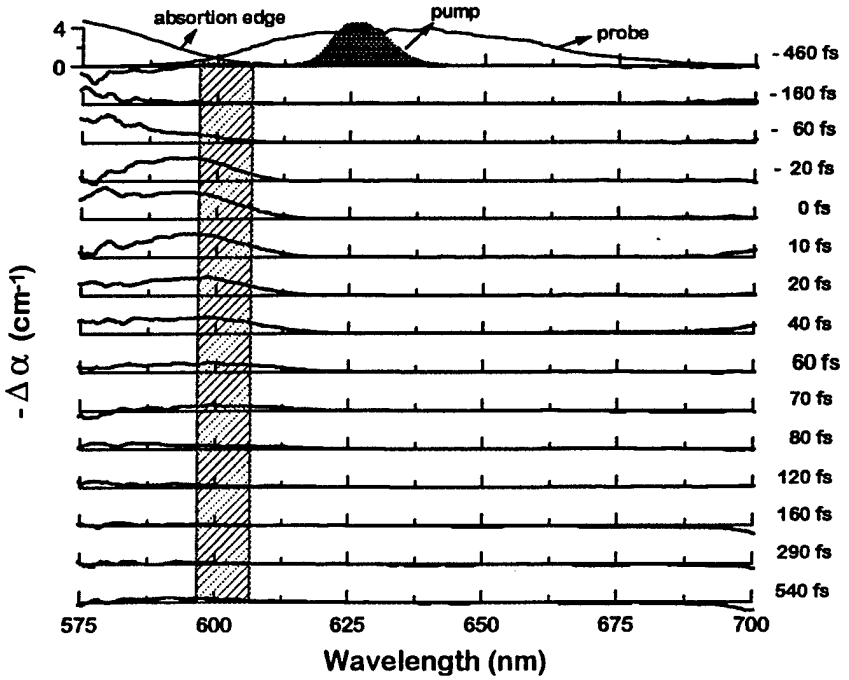

Figure 5. Differential absorption spectra for a CdSeS doped glass excited below the band edge. The upper trace shows the absorption edge, the pump spectrum and the probe pulse spectrum.

We verified that the absorption edge shifts rigidly. In the limit of a *pure shift*, the measured absorption change $\Delta\alpha$ line shape should be exactly the same as that from the derivative of the linear absorption $d\alpha/dE$. In Figure 6, $d\alpha/dE$ obtained from $\alpha(E)$, measured independently, is compared to the measured $\Delta\alpha(E)$ at zero delay. It can be seen.that the shape of the curves are very similar, which allow us to say that to a good approximation, at zero delay, the absorption edge is purely shifted to the blue.

Figure 7 shows the behavior of the absorption edge as a function of the time delay between pump and probe. The energy shift was computed as $\Delta E = \Delta\alpha\cdot(d\alpha/dE)^{-1}$, where $\Delta\alpha$ was obtained from data shown in Figure 5, using the shadowed wavelength window centered on 601 nm, and $d\alpha/dE$ is the derivative of the linear absorption curve as a function of the energy taken at 601 nm. The absorption edge is rapidly blue shifted and returns to an absorption level that is just smaller than the initial one. As mentioned before, for negative delays no changes in the spectrum are observed, which means that the remaining shift of the absorption spectrum observed at 500 fs time delay eventually recovers fully. Apart from the remaining shift at large positive delays, the profile of the shift as a function of the time delay between pump and probe pulses follows closely that of the the pump pulse.

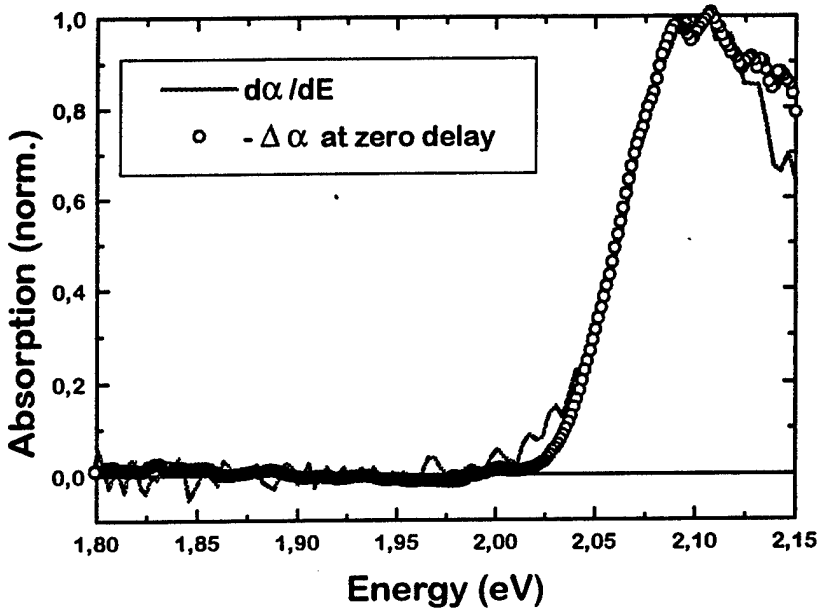

Figure 6. Measured $\Delta\alpha$ signal compared to the slope of the absorption edge, showing that the absorption edge is shifted rigidly by the pump pulse.

The behavior shown in Figure 7 is to be expected for an Optical Stark shift, where only virtual excitations are created, implying a fast response time. The residual bleaching of the absorption observed at 500 fs time delay, in opposition to what is expected from the Optical Stark effect, may be attributed to the injection of real carriers into the conduction band due to the occurrence of two-photon absorption (TPA) or residual overlap between the pump spectrum and the absorption tail. The pump pulse duration is 60 fs and for this reason the Optical Stark effect does not contribute to the signal at the 500 fs delay situation. The slow recovery component in the time response of the system must be related to band filling effects. The magnitude of this contribution to the observed signal is comparatively small. The importance of the role of real excitations in this kind of experiment was discussed elsewhere. Differently from the coherently (or virtually) driven contribution, which adiabatically follows the pump pulse, the absorbed carriers, resulting from the spectral overlap of the pump pulse and the SDG absorption or by the TPA effect, decay on a longer timescale after the pump pulse is gone and prevent the full recovery of the induced absorption change. In this situation, dynamical screening of the electron-hole interaction should be considered, since it can contribute to the bleaching of the energy shift.

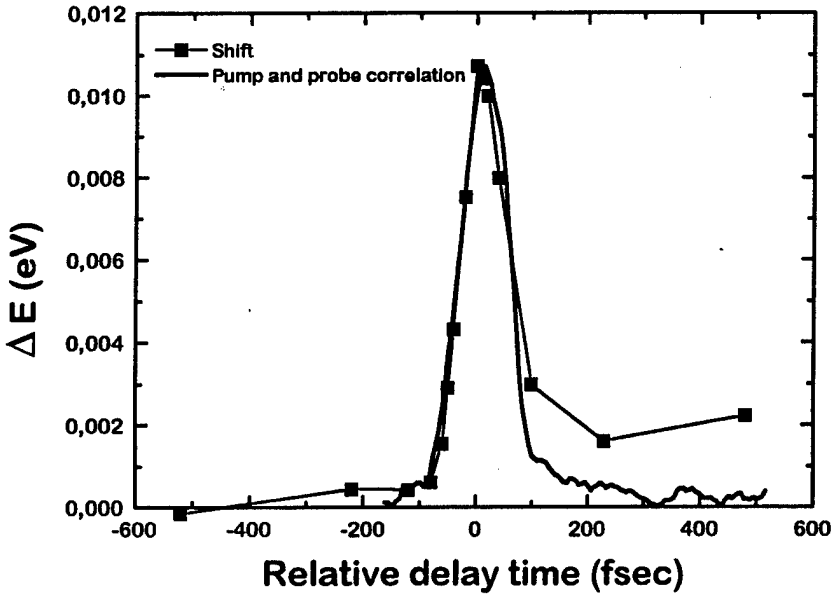

Figure 7. Time response of the absorption edge shift, showing an ultrafast response time which is limited by the time duration of the 60 fs pump pulse.

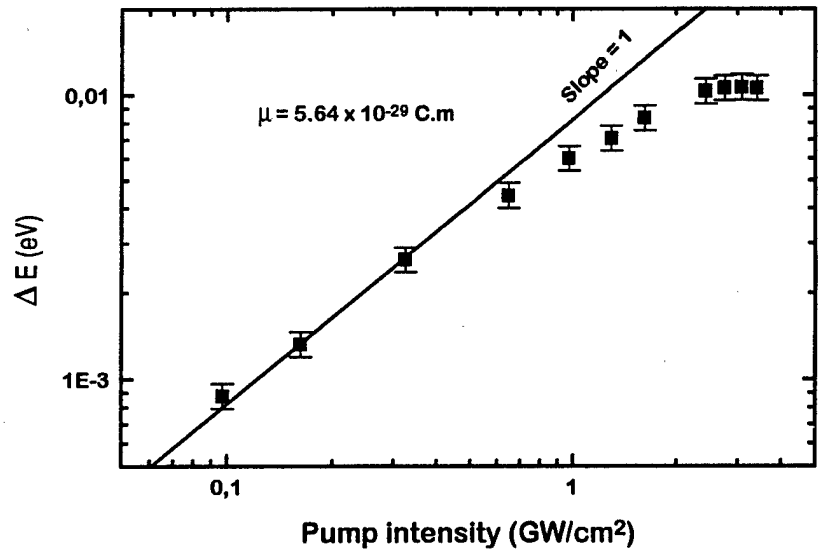

Figure 8. The measured edge shift as a function of the pump intensity.

We have also investigated the shift of the spectrum as a function of pump intensity (Figure 8). This data was obtained at zero delay, by changing the pump intensity using a variable neutral density filter in the pump beam path. Pump pulse intensities inside the crystallites ranged typically from 0.1 to 3.5 GW/cm^2.

In atomic systems, the Optical Stark effect is treated under the "dressed atom" formalism from which a blue shift of the transition lines is predicted. This picture was used by Mysyrowicz et al. [4] as a first approach to describe an observed excitonic line shift in a GaAs quantum well. In the case of a semiconductor system it is necessary to take into account the different nature of the interaction due to the formation of bound (exciton) states plus the renormalizations caused by the real or virtual carriers injected which screen the coulombic interaction [5]. The shift of the band-gap due to the presence of a pump field E_p is given, in the low field limit, by [6]

$$\Delta E_g = \frac{2(\mu_{cv} E_p)^2}{\hbar\Delta\Omega}\left[\rho_\infty + \frac{E_0}{\hbar\Delta\Omega}\nu_\infty\right] \qquad (1)$$

where $\hbar\Delta\Omega = (E_g - \hbar\omega_p)$ is the energy detuning, E_g is the energy gap, $\hbar\omega_p$ is the pump photon energy and μ_{cv} is the interband dipolar matrix element and E_0 is the exciton binding energy. The parameters ρ_∞ and ν_∞ are related, respectively, to the anharmonic exciton-photon interaction and to exciton-exciton interaction. In the case of three dimensional carriers (no confinement), their values are $\rho_\infty = 8$ and $\nu_\infty = 24$ [7].

As shown above in Figure 4, the observed shift of the absorption edge in our experiment follows the predicted linear dependence with the pump intensity for intensities up to 0.3 GW/cm^2. In this low pump intensity limit, we can calculate an effective dipole moment μ_{cv} for the SDG, using Equation 1. The application of Equation (1) to the case discussed here requires an additional averaging over the random orientation of the crystallites in the glass matrix, considering that in our experimental conditions the pump field is orthogonal to the probe field. This averaging multiplies the right hand side of Equation (1) by a factor of 1/15. The obtained value for μ_{cv} is 5.6 x 10^{-29} C.m. This compares well with the estimated values of $\mu_{cv}^{CdS} = 4.4\times10^{-29}$ C.m and $\mu_{cv}^{CdSe} = 6.1\times10^{-29}$ C.m obtained from conventional first-order perturbation calculation for direct transitions between parabolic bands [8,9]. In this approximation, μ_{cv} can be directly obtained from the band gap energy, E_g, and the electron effective mass in the conduction band [10].

At pump intensities above 0.3 GW/cm^2, deviation from the linear dependence of the shift on the pump intensity is observed. This deviation is predicted in the work of Ell et al. [7], and is related to many-body effects. As the pump intensity increases, the virtual carriers tend to spend more time in the conduction band-like states, making the screening of the Coulomb interaction more effective. This causes a renormalization of the interactions, leading to a decrease in the rate of change of the shift with respect to the pump intensity.

In conclusion, we have shown the occurrence of the Optical Stark shift in a semiconductor-doped glass on a femtosecond time scale. This is the first time to our knowledge, that the Stark shift is spectrally time resolved in this type of material. We find that at pump intensities values higher than 0.3 GW/cm^2 the Optical Stark shift in a SDG deviates from the linear dependence regime predicted for the low-intensity regime. For a pump intensity of 3 GW/cm^2 we find that the optical gap shifts by 11 meV. This behavior is in qualitative agreement with results obtained on the study of the Optical Stark effect in bulk and confined semiconductor structures. Moreover, our results confirm that the Optical Stark effect is the dominant contribution to the nonresonant third-order refractive nonlinearity of this type of SDG.

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MBE GROWTH PROCESSES AND PROCESSING TECHNIQUES APPLIED TO NOVEL DEVICE APPLICATIONS AND INTEGRATION

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We are involved in the growth of III-V semiconductor-based device structures for electronic and optoelectronic applications. Two general research areas will be discussed: (i) plamsa - enhanced molecular beam epitaxy and (ii) growth and processing techniques applicable to optoelectronic integration.

(i) InP, GaAs and InGaAsP are being grown using gas source MBE with the growing surface subjected continuously to an ECR generated plasma (H, D, He or Ar). Under some conditions the effect of the plasma is to produce quite unique material. For example, in the case of a He plasma, InP can be grown to be very resistive ($>10^5\Omega$-cm), and in both InP and InGaAsP very short minority carrier lifetimes are achieved. It is considered that the InP(He) could have application for device isolation for vertically stacked, integrated devices and possibly to form a suitable underlayer for heterojunction field effect transistors that would make them resistant to ionizing radiation effects. For the InGaAsP(He), preliminary measurements suggest it is possible to produce high-speed photodetectors (1-15ps response times) operating over a wide range of wavelengths (0.65-1.65μm).

(ii) The integration of lasers/waveguides/detectors is required for optical communications and some laser-based sensor technologies. A requirement for such integration is the production of regions of differing bandgap material. In order to avoid complicated, low reliability regrowth techniques we are exploring several approaches whereby these bandgap variations can be produced in a single growth step and may, or may not, involve subsequent process treatment. Single step processes involve selected area epitaxy onto either oxide-masked or ridge-etched substrates. Regions of different bandgap are then produced through differential surface diffusion effects. Alternately, some compositional (bandgap) changes can be produced in quantum-well structures using an oxide-enhanced diffusion process or by ion beam mixing. The current status of our work will be given.

I

Researchers at the CEMD

David A. Thompson, Director (73, Engineering Physics) received the B.Sc., (1963) and Ph.D (1967) degrees from Reading University, U.K. Graduate research involved a study of radiation damage in silicon particularly related to neutron transmutation effects. After graduation he joined the Solid State Devices Department of Westinghouse Canada, becoming Manager of Process Research and Development in 1970. There, his main duties involved developing new process technologies related to the fabrication of integrated circuits. He also held a part-time faculty appointment at McMaster University from 1969-72. In 1973, after a brief Research Fellowship at Reading University, he became an Assistant Professor at McMaster University. He was promoted to Associate Professor in 1975 and Professor in 1981. Currently he is also Director of the Centre for Electrophotonic Materials and Devices at McMaster and Programme Leader of the Optoelectronic Materials Group of the Ontario Centre for Materials Research. He is also part of two Government of Canada funded Networks of Centres of Excellence (Canadian Institute for Telecommunications Research " and "Intelligent Sensors for Innovative Structures") where he is responsible for research into smart-pixels and optical fiber strain gauges. Research activities include molecular beam epitaxial deposition of semiconductor materials and structures for optoelectronic applications and various processing technologies necessary for optoelectronic devices including ion implantation and metal-semiconductor contact formation.

Dr. Thompson has published almost 200 research articles and is a member of the Canadian Association of Physicists, Institute of Physics, the Materials Research Society, the I.E.E.E. and the Bohmische Phvsikalische Gesellschaften.

LIGHT SCATTERING AND SURFACE STEPS DURING GROWTH OF InGaAs STRAINED LAYERS BY MOLECULAR BEAM EPITAXY

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The preferred surface finish of a grown film in molecular beam epitaxy growth is a perfectly smooth surface with no flaws or texture. A variety of phenomena can cause the surface to deviate from this ideal condition including particulate contamination, kinetic roughening [1], inadequate cleaning of the substrate before growth [2] and strain relaxation in a non-lattice-matched film [3]. Frequently the surface imperfections scatter enough light that they can be detected by eye when the film is illuminated by intense white light. This simple qualitative inspection of the film can be made more quantitative and sensitive by using a collimated laser beam as the incident light soource and a photodetector to measure the scattered light. Laser light scattering (LLS) has the additional virtue of being well-suited to real time measurements during film growth.

Provided the surface is not too rough the intensity of the light scattered into the plane of incidence from a beam of light of wavelength λ incident on a rough surface at an angle θ_o with respect to the surface normal, is given by [4],

$$\frac{dP}{Pd\Omega} = \frac{16\pi^2}{\lambda^4} cos\theta_o cos^2\theta_s Q^2(\theta_o,\theta_s) g(\boldsymbol{q}) \qquad [1]$$

where θ_s is the angle of the scattered light, λ is the wavelength of the light, P is the intensity of the incident light, $d\Omega$ is the solid angle of the scattered light, Q is an angle-dependent factor which reduces to the usual Fresnel coefficient when $\theta_o = \theta_s$. $g(\boldsymbol{q})$ is the power spectral density of the surface morphology at spatial freqency $\boldsymbol{q}$. For scattering in the plane of incidence,

$$q = \frac{2\pi}{\lambda}(sin\theta_o - sin\theta_s) \qquad [2]$$

In the case of interest here $\theta_o = 25°$, $\theta_s = 90°$, and $\lambda = 488$ nm. (The angle of incidence is set by the orientation of the effusion cell ports on a VG MBE system.) For this wavelength and these angles q = 5.4 μm^{-1} and Q = 0.6 for a GaAs substrate and s-polarized light.

As an example of the application of light scattering to measurements of surface morphology during thin film growth we consider the growth of $In_{0.2}Ga_{0.8}As$ strained layers on GaAs substrates. Initially the deposited InGaAs layers are compressively stressed to match the lattice constant of the underlying GaAs substrate. Eventually as the deposited film increases in thickness the strained film is unstable against the formation of misfit dislocations at the interface between the substrate and the deposited film. This could occur for example by threading dislocations bending over into the plane of the interface. Due to the asymmetry in the elastic properties of the crystal lattice, the misfit dislocations are found to lie in two orthogonal directions, parallel to the [110] and [1 $\bar{1}$ 0] directions. In addition because the slip associated with the misfit dislocations must lie along a <111> direction, each misfit dislocation has associated with it a component of the slip that is

perpendicular to the surface, for [100] oriented substrates. This means that a surface step is produced with each misfit dislocation.

Fig.1 shows the intensity of the light scattered from the substrate as a function of thickness during growth of $In_{0.2}Ga_{0.8}As$ on a GaAs (100) substrate. The two curves correspond to the plane of incidence oriented parallel to the [110] and [1 $\bar{1}$ 0] directions. The abrupt rise in the scattered light intensity corresponds to the onset of strain relaxation through creation of misfit dislocations.

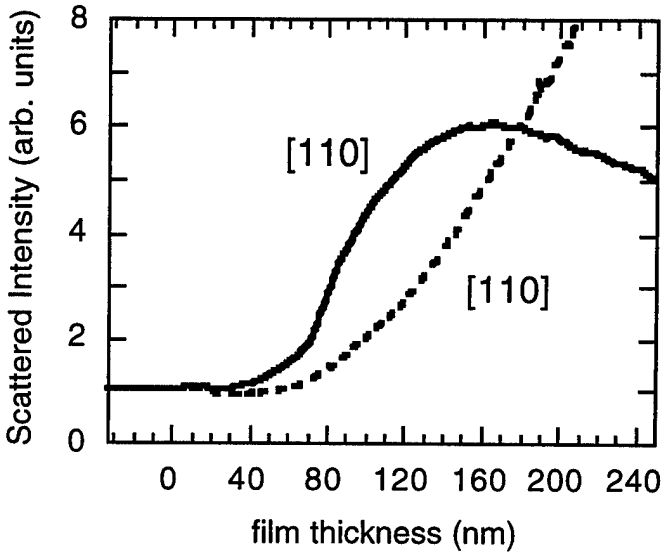
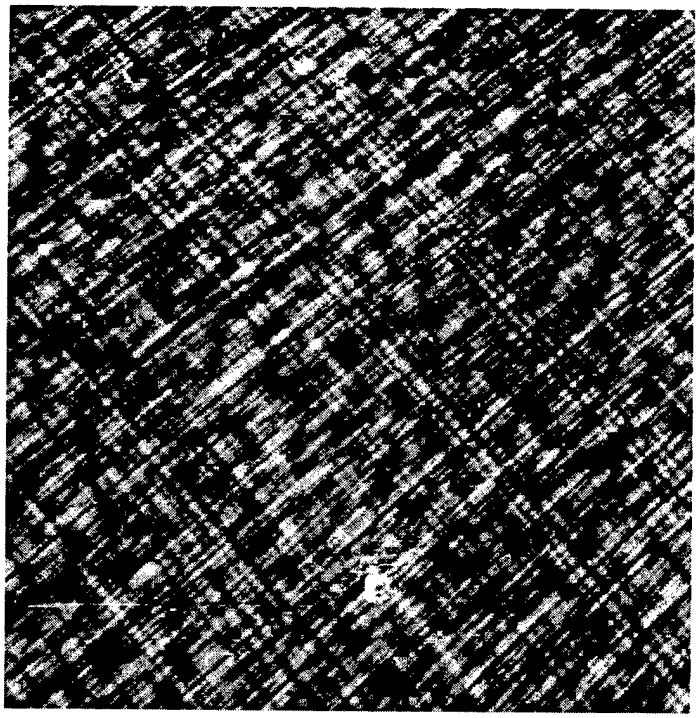


Figure 1 Scattered light intensity in the plane of incidence during growth of InGaAs on GaAs with the plane of incidence aligned parallel to the [1 $\bar{1}$ 0] direction (solid line) and the [110] direction (broken line). Time zero corresponds to the start of growth on a GaAs buffer layer.

A scanning force microscope (SFM) image of a partially relaxed 250 nm thick InGaAs film grown on GaAs is shown in Fig. 2(a). The cross-hatch pattern that is clearly visible in this image is associated with the two orthogonal sets of misfit dislocations. The power spectral density for this image is shown in Fig. 2(b). In this figure the "X" pattern comes from taking the Fourier transform of the two sets of orthogonal straight lines observed in Fig. 2(a). The two diagonal lines making up the cross pattern in the Fourier transform image in Fig. 2(b) are broadened by distortion in the SFM scanner mechanism. This broadening is not present in the light scattering from similar samples which also shows a cross pattern in the scattered light distribution except that the width of the lines in the cross in the scattered light distribution is reduced compared to the SFM data and limited by the angular divergence of the incident laser beam.

The surface steps associated with the misfit dislocations can be easily detected with light scattering. To demonstrate this we use Eqn. 1 to estimate the scattered light intensity for a surface with oriented steps. To facilitate the calculation we assume that the surface is perfectly flat with a random distribution of alternating up and down steps that are oriented parallel to the [110] and [1 $\bar{1}$ 0] directions and extend to infinity. If the plane of incidence is oriented so that it is

(a)



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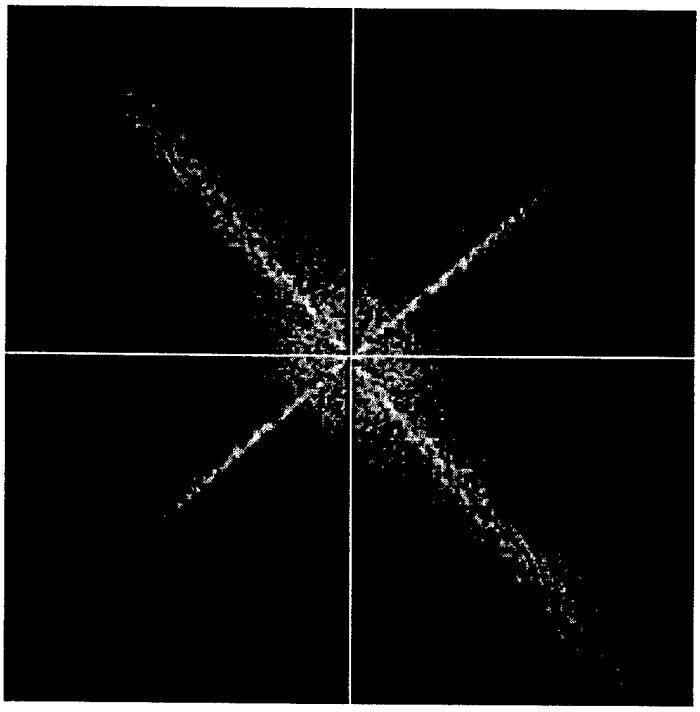

Figure 2 (a) Scanning force microscope image of the surface of a relaxed InGaAs layer on GaAs, and (b) power spectral density for the image in (a). The image in (a) is 50 μm wide and the vertical gray scale is 5 nm. The power spectral density in (b) extends from - 19 μm^{-1} to 19 μm^{-1} and [110] points up to the left.

perpendicular to one of the families of steps then these steps will scatter light in the plane of incidence. To estimate the intensity of the scattered light as a function of scattering angle we need to know the one dimensional power spectral density of the surface in the direction perpendicular to the steps on the surface. This can be readily obtained if we note that the surface structure for our model has the form of a random telegraph signal [5]. In this case,

$$g(q_x,q_y)=\frac{a^2 s}{q_x^2+4s^2}\delta(q_y) \qquad [3]$$

were we have included only one of the two orthogonal families of steps for simplicity. In this expression the steps have height a, their density is s steps per unit length and they are assumed to be perpendicular to the x direction.

Since the angular resolution of the detector in an experiment will be greater than zero, the δ function which describes the scattering parallel to the surface steps will be integrated by the solid angle of the detector. In this case the scattered intensity at the detector will only depend on the angular size of the detector in the plane of incidence, $\Delta\theta_s$:

$$\frac{\Delta P}{P}=\frac{16\pi^2}{\lambda^3}cos\theta_o cos^2\theta_s Q^2(\theta_o,\theta_s)\frac{a^2 s}{q_x^2+4s^2}\Delta\theta_s \qquad [4]$$

The maximum scattering intensity will occur when the average periodicity in the surface matches the momentum transfer in the light scattering process, or when $2s = q_x$. In our case since $q_x = 5.4 \times 10^4$ cm^{-1}, the light scattering is most sensitive to steps with an average spacing of $s^{-1} = 2/q_x = 0.37$ μm. Using the angles and wavelength given above, a detector acceptance angle of 0.08 rad, and a step height of 0.28 nm the scattering probability $\Delta P/P = 1.4 \times 10^{-7}$. For an incident beam intensity[3] of 27 mw, this scattered intensity is easily detectable. The main experimental problem is not the detection of the scattered light but rather minimizing the scattered light background from other optical elements in the system. Nevertheless the calculated scattering intensity by the atomic steps on the surface is readily measureable since the scattered light background can be orders of magnitude smaller. For example a ratio of 10^{11} between the specular beam and the scattered beam has been achieved in scattering measurements in a MBE system.[6]

In this report we show that one dimensional arrays of individual surface steps on smooth surfaces can be easily detected by light scattering. For maximum sensitivity the average spacing of the steps on the surface should be on the order of the wavelength of the light. The detection sensitivity is sufficiently high that it should be possible to detect steps whose average spacing is one or two orders of magnitude bigger or smaller than a wavelength.

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Research Program on Ultrafast Optical Phenomena and Optical Communications at Unicamp

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A brief description is given of research activities on Ultrafast Phenomena and Optical Communications currently in progress at Unicamp. These activities cover new glass and polymer materials for photonics, nonlinear optics and femtosecond processes studies on these materials, photonics devices such as Erbium Doped Fiber Amplifiers, and applications in high bit rate optical communications.

The purpose of this article is to introduce our Group on Ultrafast Phenomena and Optical Communications and describe our objectives and current research activities. We hope to facilitate the identification of common interests for international collaborations. We are investigating new concepts and technologies with potential applications in optical communications.

Our group was formed in 1975 to develop optical fibers for the government agency TELEBRAS (Telecomunicações do Brasil). This development was successful and today most of the optical fiber produced in Brazil use our technology. Along the 20 years of our existence, various of our developments and "know how" have been transferred to Brazilian industries, such as Optical Fiber Couplers, characterization procedures, and Erbium Doped Fiber Amplifiers. Our general objective has been to participate of the Brazilian effort for the independent development of optical communications and photonics, providing specialized human resources at all levels from technicians to PhD's, laboratories for special tests and measurements, and monitoring of emerging technologies.

A very simplified description of our activities is given in this paper. Further information can be obtained through our web home page at http://www/ifi.unicamp.br/gfurco.

Our research program involves four principal activities: Optical communications, New materials, Nonlinear optics, and Femtosecond phenomena. In the **New Materials** area, we develop glasses doped with quantum dots (CdTe, PbTe) for all optical switches, as well as special glasses (Telurites, Chalcogenides, Niobates) doped with rare earth ions (Er^{3+}, Yb^{3+}, Pr^{3+}) for optical amplifiers. These glasses can accommodate high doping levels of rare earth's and are compatible with fabrication processes of optical fibers or planar waveguide integrated optical amplifiers and lasers.

In the field of **Optical Communications** field we collaborate with TELEBRAS in studies of high bit rate systems (> 2.5 Gb/s), impact of optical nonlinearities in fiber communications, and components for 1.5 μm systems such as Erbium Doped Fiber Amplifiers (EDFA) and soliton laser sources. In this field we also monitor advances in optical communications technology to recommend strategies for future upgrades of Brazilian optical links.

Presently we are developing novel and efficient methods of characterization of Erbium Doped Fibers (EDF) for optical amplifiers and lasers.[1] An example of an accurate method for measuring the saturation power of EDF's is given in fig. 1.[2] The objectives of these activities are (1) to support design optimization of the EDF's tailored for specific applications (low noise preamplifiers, high output power boosters, etc.) and (2) to provide fully automated EDF characterization procedures for specifications and quality control, as a support for the Brazilian industries that acquired the EDFA technology from TELEBRAS.

Other developments under progress in our group are new laser configurations operating at 1.5 μm. This activities include laboratory explorations of Gain Switched laser diodes as inexpensive devices for high bit rate systems, externally modulated lasers for high quality soliton sources, and high power Cavity Dumped harmonically mode-locked EDF lasers for nonlinear optics experiments.

We also perform fiber loop tests for laboratory simulations of long distance transmissions at high bit rates using EDFA. This activity is directed to evaluate the impact of nonlinear optical effects in different types of fibers and the performance of components such as modulators, filters, isolators, high power

transmitters and booster amplifiers in long distance fiber communications, and to explore new transmission concepts such as solitons.

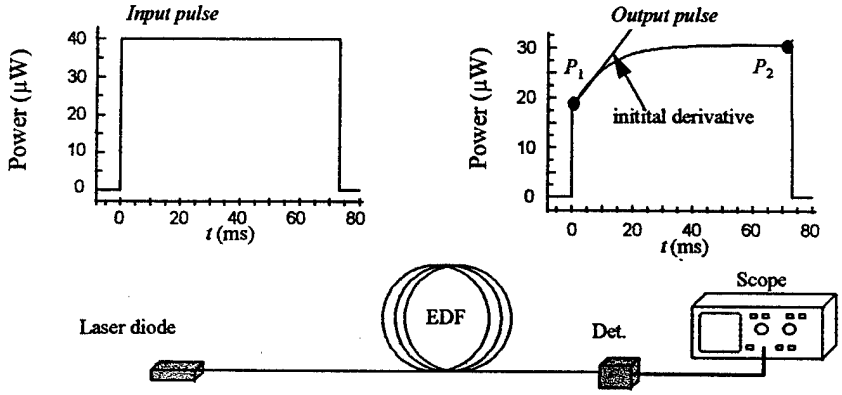

Fig. 1. Fast and nondestructive method for characterization of the intrinsic saturation power of Erbium Doped Fibers (EDF) developed at our group. A flat top pulse is launched into the EDF and the output pulse waveform is measured with a digitizing oscilloscope (an actually measured pulse is represented in this figure). The linear (P_1) and saturated (P_2) transmitted outputs are simultaneously displayed in the scope; from these values and the initial time derivative, the intrinsic saturation power is determined by using $P_{sat} = (P_2 - P_1)/[\tau d(\ln P_1)/dt - \ln(P_2/P_1)]$ (τ is Erbium excited state lifetime).

In the field of **Nonlinear Optics** our activities are directed to answer the very basic question of what makes a given optical material more nonlinear than others and identify materials for photonics switching applications. We investigate (experimentally and theoretically) the nonlinear optical properties of new materials such as Semiconductor Doped Glasses (SDG) and Organic Polymers in their regions of high transparency.

We measure the nonlinear refractive index (n_2) and the two photon absorption (TPA) coefficient (β) which determine, respectively, the real and imaginary parts of the third order optical susceptibility $\chi^{(3)}$. For all optical switching applications we qualify the materials at a given wavelength (λ) according to the two photon figure of merit $F = n_2/\lambda\beta$ and other qualifiers such as the linear losses, switching power, group velocity dispersion (GVD), response time, optical quality, photo-stability, and so on.[3] A candidate material for a nonlinear directional coupler device (which is of most interest for optical communications) must have $|F| > 2$.[4]

In SDG's the nonlinearity depends on quantum confinement and we are presently investigating how F depends on the size and transition frequencies of the quantum dots (QD). For a given material, larger crystallites exhibit less quantum confinement but larger n_2. In the limit of crystallite radius >> exciton Bohr radius (or 7 nm for CdTe) the SDG behaves like the bulk semiconductor, with a large figure of merit for photon energies below but close to the band gap[5] (the dominant nonlinearity being the optical Stark shift effect) or below but close the TPA gap (two photon enhancement of $\chi^{(3)}$). An advantage of SDG over bulk semiconductors is that the GVD is much smaller in the first, thus introducing less pulse broadening and chirp.[6] In the region of $\chi^{(3)}$ dominated by the optical Stark shift, the linear losses and GVD are large and in the region below the two photon gap, n_2 is too small. Smaller crystallites, on the other hand, the strong quantum confinement concentrates the oscillator strength of the QD transitions in narrow spectral regions and, if size dispersion can be controlled,[7] one can get close to the resonances without increasing linear or TPA losses.

In commercially available SDG's the electronic third order susceptibility is often masked by the presence of traps and photodarkening effects which dominates the nonlinear response and can even change the sign of the measured nonlinear refractive index (see Figure 1).[8] These SDG's show weak quantum confinement. In the case of our SDG of CdTe, the presence of traps can be reduced by special treatments.[9] This material, with strong quantum confinement, has the largest n_2 of all SDG's in the transparency region so far reported.[10]

Another property of CdTe SDG is that it exhibits a lifetime of the QD excited state which is fast (sub-

picosecond) and depends on the size of the nanocrystal. For some QD radii the relaxation is extremely fast (360 fs lifetime for 2 nm radius) and complete (no background or slow process after the main decay).[7] We believe that this material is very attractive as a fast saturable absorber for laser pulse shaping and photonic switching using saturable absorption applications.

For photonic switching based on saturable absorption with applications in optical communications we have recently developed quantum dots of PbTe,[11] with QD transitions occurring in the 1.5 μm region, where optical fibers present the minimum loss and where the Erbium doped fiber amplifiers operate. This development opens new possibilities for photonic switching.

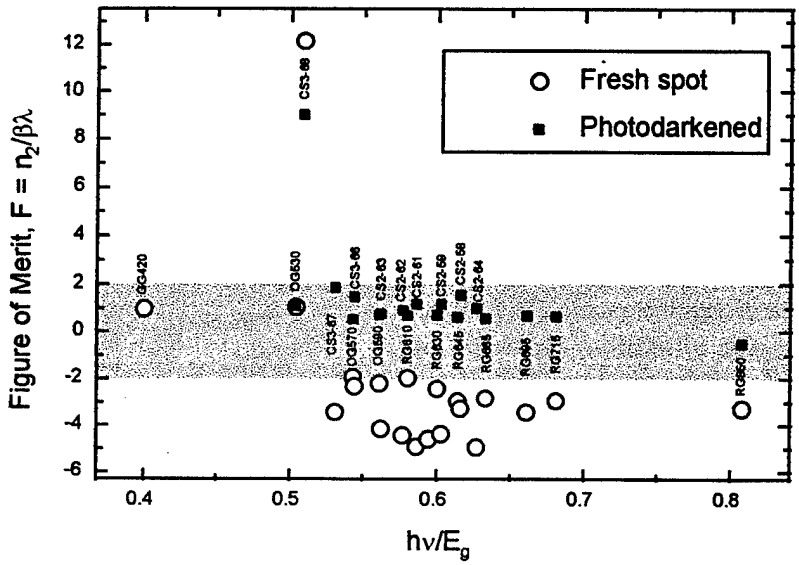

Fig. 2. The two photon figure of merit (from measurements of n_2 and β at λ = 1 μm) for several commercially available SDG color filters before and after partial photodarkening. Data points are organized as a function of the parameter $h\nu/E_g$, where E_g is the optical band gap energy and $h\nu$ is photon energy of the measurement laser. Labels close to the data points are trade names from Corning (CS) or Schott (RG and GG).

Polymers doped with conjugated chromophores exhibit a nonlinear refractive index in the transparency region which is even larger than those of SDG's. In this case n_2 scales with the concentration of the chromophores. By physically doping PMMA (Polymethyl Methacrylate) polymer films with DR1 (Disperse Red 1 dye), for example, we measured (at λ = 1.06 μm) $n_2 = 3.2\times10^{-12}$ cm^2/W at the maximum concentration.[12] By chemical doping (functionalized or side chain co-polymerization) of the same chromophore in the same MMA (Methyl Methacrylate) monomer, we measured $n_2 = 5.3\times10^{-12}$ cm^2/W. The larger n_2 is due to a larger concentration of chromophores in the chemically doped polymer, which is not limited, as in the physically doped case, by the solubility of the dye. Our studies indicate that Organics exhibit larger n_2 and larger figure of merit (F) than SDG's but they have less photo-stability and the optical quality is lower.

Material	$\|n_2\|$ (cm^2/W)	P_π (W)
Silica	3×10^{-16}	2×10^{4}
Cd(S,Se) SDG	5×10^{-15}	1×10^{3}
CdTe SDG	5×10^{-14}	1×10^{2}
DR1-MMA copolymer	5×10^{-12}	1×10^{1}

Table I. Nonlinear refractive index at λ = 1 μm for various materials and the Switching Power ($P_\pi = \lambda\ell A/n_2$), defined as the power required to induce a phase shift of π in an optical beam (or waveguide) with ℓ = 1 cm long and $A = 10^{-7}$ cm^2 cross sectional area. The value of n_2 quoted for Cd(S,Se) is representative of our measurements on commercially available color filters from Corning, Jena and Schott.

Still another activity of our group in collaboration with TELEBRAS is the study of electro-optical properties of **poled polymer films**. Polymers doped with optically nonlinear chromophores are attractive for electro-optical switching devices at high bit rates,

as an alternative to Lithium Niobate devices. We develop films and planar optical waveguides of MMA (Methyl Metha Acrylate) copolarized with pendant groups or crosslinked chromophores which are poled in an electric field during the fabrication processes. We study the time decay of the molecular orientation of chromophores, which is generally attributed to thermal and free volume relaxation. We have recently observed in azo type chromophores light induced changes in molecular orientation through a processes which is most likely due to photoisomerization. From these measurements we concluded that common laboratory light intensity levels provides a significant contribution to the total orientational relaxation rate.[13]

In the field of **Ultrafast Phenomena** we use time resolved spectroscopic techniques with 10 fs laser pulses to investigate the relaxation dynamics of quantum dots and bulk semiconductors. From hole burning measurements with femtosecond resolution and excitation spectra[14] (which are QD size selective) we are able to determine the energy levels of our CdTe quantum dots. An advantage of using femtosecond pulses is that we can time resolve the different contributions to the optical nonlinearities of materials. In particular, we can discriminate the fast electronic response from slower thermal or trap contributions. For example, using femtosecond pulses we clearly observe the optical Stark effect in SDG's and thus measure the QD transition dipole moment which determines the nonlinear refractive index near the band gap. A more detailed description of our activities in this field is presented by C.H. Brito Cruz this Proceedings.

Our work is supported by the Brazilian agencies TELEBRAS, PADCT, RHAE, FAPESP, CAPES, FAEP, FINEP and CNPq.

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ABSOLUTE FREQUENCY CONTROL FOR MULTIFREQUENCY OPTICAL COMMUNICATIONS

by

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Summary

Multifrequency (multiwavelength) optical communications systems are considered as a means to increase the throughput for point to point fiber links. It is also suggested to use the frequency as the key identification element for routing in meshed networks. With increasing frequency density both applications will require a precise control of each laser frequency to avoid crosstalk or wrong identification.

At Laval University, we have devised techniques that allow the precise setting of laser frequency to absolutely known values. Semiconductor lasers frequency-locked to atomic rubidium [1-7] or molecular acetylene absorption lines [8] have been extensively studied as master lasers. Absolute frequency settings with relative precision of a few part per billion (10^{-9}) have been achieved [9].

We have developed two techniques that translate the properties of these master lasers to other lasers at nearby frequencies. In a first set of experiments, we have studied the use of multimode optical resonators to supply evenly spaced optical frequency references for laser frequency-locking purpose. A method has been devised to calibrate absolutely the free spectral range of a Fabry-Pérot resonator and to lock laser frequencies to its various transmission modes [10]. At the time of this demonstration, it has been shown that the ultimate precision was limited by the knowledge of the absolute frequency reference used for the calibration [11].

In a second approach, a surface emitting multilayered nonlinear crystal has been used as a frequency offset sensor to measure the frequency difference between a master laser and a laser to be controlled [12-14]. Absolute frequency setting can be achieved to any value with a precision of 250 MHz.

Since the Fabry-Pérot referencing element and the multilayered nonlinear crystal operate as well in the 1300 nm and 1550 nm bands, we have shown that both techniques can be used to control simultaneously the absolute frequency of lasers operating in either bands [15].

For standardization purposes, we have also proposed the use of a frequency referencing scale with settings at exact multiples of 100 GHz [16]. A possible realization using an absolutely calibrated Fabry-Perot resonator has been demonstrated [17]. This proposal is now made to the International Telecommunication Union as the recommended frequencies within the transmission band of Erbium doped fiber amplifiers (191.7 THz to 195.9 THz with 0.1 THz spacing)!

A test bench for the study of multifrequency optical communications phenomena has been built in our laboratory. This test bench includes four intensity-modulated lasers-transmitters with absolute frequency control, an Erbium doped silica fiber amplifier, an in-fiber chirped Bragg-grating dispersion compensator and an all-fiber selective filter. The study of nonlinear phenomena associated with the transmission of multiple frequency signals over long haul links is now under progress.

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Michel TÊTU is a professor at the Electrical Engineering Department of Université Laval since 1974. His research activities have been concerned with the development of atomic frequency standards. He contributed to the establishment of theoretical tools and mesurement procedures for their frequency characterization. His work is now aiming at the realization of precise optical frequency standards based on semiconductor lasers for applications to multiwavelength communications, microwave technology and optical instrumentation.

Dr. TÊTU is member of the Optical Society of America, the Institute of Electrical and Electronics Engineers, the American Physical Society, the International Society of Optical Engineers, the Canadian Association of Physicists and the professional engineers' association, "Ordre des Ingénieurs du Québec".

Progress in Free Space Optical Backplanes

by

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Abstract

Progress in smart pixel based free-space optical backplanes is described. System experiments are described, including both enabling technology development and demonstrator performance results. Future system demonstrators are also discussed.

Introduction

Future digital systems such as ATM switching systems and massively parallel processing computer systems will have large Printed Circuit Board (PCB) to Printed Circuit Board connectivity requirements to support the large aggregate throughput demands being placed on such systems.[1] Current electronic technology may not be capable of supporting both the connection densities and the bandwidth required due to connector limitations at the PCB to backplane interface.[2] Two-dimensional, free-space optical interconnects represent a potential solution to the needs of these connection-intensive digital systems. When implemented at the PCB-to-PCB level in the form of an optical backplane, this technology is potentially capable of providing greater connectivity at higher data rates than can be supported by current or projected electronic backplanes. An optical backplane can be constructed using two-dimensional arrays of passive, free-space, parallel optical communication channels which optically interconnect PCBs via smart pixels arrays. The smart pixel optoelectronics are two dimensional device arrays capable of electrical-to-optical (E/O) and optical-to-electrical (O/E) conversion of digital data. In addition to the E/O and O/E conversion, these devices can perform processing operations at the backplane level such as address recognition, or packet routing. By interconnecting PCBs with 10,000 channels/board (10 smart pixel arrays per PCB at 1000 communication channels per smart pixel array), each channel running at 100 Mb/s will support greater than a TeraBit/sec of aggregate data traffic.

The identification of critical research issues in optical backplanes is being pursued in the form of system demonstrator experiments. This paper describes a number of smart pixel based system demonstrators which have either been constructed, or are currently planned, which highlight the application of free-space digital optic technology in optical backplanes.

A FET-SEED Based Optical Backplane Demonstrator System

An optical backplane demonstration system was constructed using FET-SEED smart pixels and free-space optics to interconnect PCBs in a two board, unidirectional link configuration.[3] 4 x 4 arrays of FET-SEED transceivers pitched at 200 μm were designed, fabricated, and packaged at the PCB level. The optical interconnection was constructed using diffractive microoptics, and custom optomechanics.

The system was operated in two configurations. Based on the 600 μm center-to-center spacing of the lenslets arrays, in the first configuration the 4 corners of the transceiver arrays were interconnected optically. In this configuration, each lenslet supported one dual rail optical channel. The system was operated in this configuration at data rates up to 100 Mb/sec on each individual channel. No significant optical crosstalk was detected in the system. In the second configuration, a single

lenslet (600 μm in diameter) was used to support four dual rail optical channels, a total of eight optical channels, in a Cluster Pixel configuration. In this mode the system was operated at 25 Mb/s simultaneously on all four channels. This result was significant in that it demonstrated a connection density of 2222 channels/cm^2.

A VCSEL/MSM Based Optical Backplane Demonstrator

A second demonstrator system capable of interconnecting PCBs using custom optics and optomechanics integrated into a standard electronic backplane chassis was constructed. This system was a 16 channel PCB-to-PCB optical interconnect which utilized VCSELs and hybrid MSM/Transimpedence amplifiers to form smart pixel transceiver arrays. The 4x4 optoelectronic device arrays were pitched at 125μm, and packaged at the PCB level using high speed board level packaging. The optical interconnect was achieved using a bulk optic based 4f telecentric relay. Custom barrel based optomechanics were designed and integrated into a standard VME backplane chassis. The system operated in excess of 250 Mb/s on each of the 16 channels serially, and at 155 Mb/s on 11 channels in parallel. Based on the pitch of the optoelectronics, the system demonstrated a connection density of > 6000 channels/cm^2, and remained operationally aligned for over three weeks.[4]

A CMOS/SEED Based Optical Backplane Demonstrator

A third demonstrator is currently being designed and will be operational by early 1996. This system will include CMOS/SEED smart pixel arrays, diffractive microoptics, and custom VME chassis optomechanics. The system will be capable of interconnecting four printed circuit boards on 16 optical channels. This system represents an aggressive multi-stage system designed to further highlight the utility of free-space digital optic technology in optical backplanes.

Conclusions

In conclusion, we have constructed a series of optical backplane demonstrator systems capable of PCB-to-PCB optical interconnection. In each system, digital data, fed onto a PCB, was optically encoded, transmitted, demodulated, and read out electrically. Smart pixel transceiver arrays were used for the E/O and O/E conversion. Free-space optical communication channels were established using either bulk or diffracitive optics. Operational testing of the systems demonstrated large bandwidths and high connection densities. Future demonstrators will expand on these results by increasing the number of stages, and by implementing sophisticated architectures such as the Hyperplane which utilizes the increased connectivity provided by an optical backplane.[5]

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Optical Properties of $Al_xGa_{1-x}As/In_{0.15}Ga_{0.85}As$ Strained-Layer Quantum Well Structures Grown on (111)B Substrates}

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Abstract

We have used the full quantum confined Stark effect (full QCSE, i.e., both a blue then a red shift with increasing reverse bias) to measure the strain-induced electric field in AlGaAs/InGaAs quantum well (QW) structures grown on (111)B substrates. The magnitude of this field, at room temperature, is lower than that expected from bulk piezoelectric theory. Moreover, its magnitude varies significantly with temperature from 4 K to 470 K. In contrast, similarly grown GaAs/InGaAs QW structures have such shallow wells that their optical transitions do not exhibit the full QCSE so that the corresponding piezoelectric properties can not be easily measured. Both calculations and optical studies show that the carriers are loosely confined and tunnel out of the GaAs/InGaAs quantum wells before the full QCSE is realized.

Summary

We have been studying InGaAs strained layer quantum well (QW) structures grown on (111)B substrates in order to understand some of the physical properties unique to this material system. A small biaxial strain, (e.g., on the order of 1%) in the (111) plane, results in a polarization field of about 200 kV/cm that points in the [111] direction.[1] Thus, by placing an AlGaAs/InGaAs QW in the intrinsic region of a p-i-n diode grown on an n^+ (111)B GaAs substrate you produce the situation that an increasing reverse bias will decrease the electric field in the QW. The electric field decreases from a finite value to 0.0 V/cm and then increases but in the $[\bar{1}\,\bar{1}\,\bar{1}]$ direction. As a result of this situation, optical transitions will initially shift toward the blue, with increasing reverse bias (i.e., as the QW electric field vanishes) and then shift toward the red with still further increases in reverse bias (as the QW electric field increases). This "Full" quantum confined stark effect (QCSE) can only be observed in strained-layer QW structures grown along polar axes where the biaxial strain (in the layer of the QW) gives rise to a shear strain in the crystal axes.

We have devised an optical method of measuring the strain-induced electric fields in AlGaAs/InGaAs QWs grown on (111)B substrates.[2] Also, we observed that it varies significantly with temperature, a result quite unexpected for the III-V materials system that has T_d.[3-4] However, the symmetry of the QW is actually reduced to C_{3v} because of its finite extent in the growth direction and the p-i-n field. With this in mind, we intended on measuring the piezo/pyroelectric effects in similarly grown GaAs/InGaAs QW structures. As it turned out, the GaAs/InGaAs QW structures had optical properties that were quite different that the AlGaAs/InGaAs QW structures and similar measurements were not possible.

The differences in the optical properties between the AlGaAs/InGaAs samples and the GaAs/InGaAs samples are attributed to carrier confinement. The AlGaAs provides a barrier that is on the order of 300 meV while the GaAs barrier is only about 75 meV above the bottom of the InGaAs QW. At 0.0 volts bias, for example, the GaAs/InGaAs sample has about a 375 Å barrier on the low energy side of the QW and the AlGaAs/InGaAs sample has about an 800 Å barrier. In both cases the carriers are confined. At -3.0 volts bias, the former sample has only about a 60 Å barrier whereas the latter sample has a 300 Å barrier. At this bias, the carriers can easily tunnel out of the GaAs/InGaAs QW but are still confined in the AlGaAs/InGaAs sample.

The confinement, or lack thereof can explain the differences in the optical properties of the 2 types of samples discussed here. For the sake of brevity only photoluminescence (PL) experiments are discussed in this summary. For samples with AlGaAs barriers, the PL peak associated with first heavy-hole transition increases in intensity and shifts toward the blue as the reverse bias increases, (the electric field in the QW initially diminishes). The blue shift results from the quantum confined stark effect. The magnitude of the PL peak increases because the overlap between the electron and hole increases as the electric field in the QW decreases. As the QW is biased passed flat band (i.e., the electric field in the QW increases in but in the opposite direction) the PL peak shifts toward the red and diminishes in magnitude. In the case of the sample with GaAs barriers, the corresponding PL peak increases in magnitude and shifts toward the blue. However, its magnitude begins to diminish well before flat band in the QW is attained. This is evidenced by the continual blue shift as the feature grows smaller. The diminution occurs, in spite of the decreasing electric field in the QW, because the overlap of the wavefunctions decreases as the carriers tunnel out of the QW.

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Quantum Well Intermixing for the Realization of Photonic Integrated Circuits

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ABSTRACT

A technique, based on quantum well (QW) intermixing, has been developed for the post growth, spatially selective tuning of the QW bandgap in a laser structure. High energy (MeV) ion implantation is used to create a large number of vacancies and interstitials in the device. During high temperature processing, these defects simultaneously enhance the intermixing of the QW and the barrier materials, producing a blue shift of the QW bandgap, and are annealed out. Increases in bandgap energy (measured using low temperature photoluminescence spectroscopy) of greater than 60 meV can be achieved. Absorption spectroscopy in the waveguide direction is also used to quantify any excess loss in the structure. Using a simple masking scheme to spatially modify the defect concentration, different regions of a wafer can be blue shifted by different amounts. This allows the integration of many different devices such as lasers, detectors, modulators, waveguides etc. on a single wafer using only a single, post-growth processing step. The performance of both passive (waveguide) and active (laser) devices produced using this technique is described, as well as the practicality of this technique in the production of photonic integrated circuits.

Keywords: photonic integration, quantum well intermixing, bandgap shifting, ion implantation

1. INTRODUCTION

Recently, there has been a great deal of effort expended attempting to integrate optical components with different functionalities, e.g. lasers, detectors, modulators, low-loss waveguides, etc., on a single wafer in a monolithic fashion. Photonic integrated circuits (PICs) will simplify the production of sophisticated optoelectronic circuits resulting in improved reliability and reduced cost. A defining requirement for the fabrication of PICs is control of the bandgap energies among the various components.

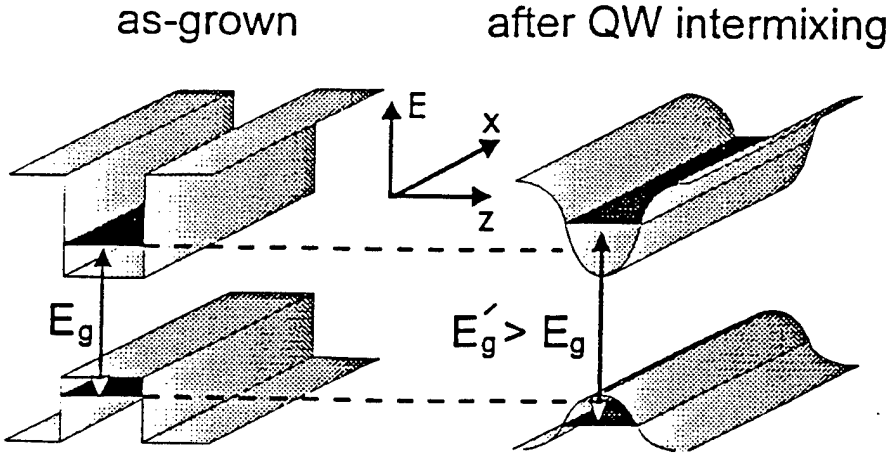

Figure 1: Schematic diagram illustrating the effect of quantum well shape modification on QW bandgap energies.

For example, the bandgap energy requirements of a circuit consisting of a quantum well (QW) laser, electro-absorptive modulator, and a transparent waveguide are that the bandgap energy of the laser must be lower than that of the modulator, which is, in turn, lower than that of the waveguide. This necessitates a technique that permits accurate control the bandgap energy in a spatially selective manner across a wafer. The most versatile technique for doing this involves complicated etch and regrowth processes or special growth techniques. In the case where a single QW active layer can be used, these layers are etched from regions where they are unwanted and the structure is overgrown with the same upper cladding layers but a different active region.[1,2] This is possible in principle but very difficult in practice.

Another technique, which is generating considerable interest due to its simplicity, is the fabrication of integrated optoelectronic devices using spatially selective modification of QW shapes.[3-14] This is based on the fact that a QW is an inherently metastable system due to the large concentration gradient of atomic species across the QW/barrier interface. For example, in the InGaAs/InGaAsP QWs studied in this work, the phosphorus concentration changes from 43% to 0% in a distance of less than 1 nm. At temperatures above 750 °C significant diffusion of atomic species will occur resulting in an intermixing of the QW and barrier materials, shown schematically in Figure 1. This process causes a rounding of the initially square QW energy profile, and, in general, results in an increase of the bandgap energy.[15] This process can be greatly enhanced by the presence of impurities or defects in the vicinity of the QW, allowing intermixing to occur at temperatures that are significantly lower than that normally required. Various techniques, such as impurity induced disordering[4,9,10], laser beam induced disordering[13], impurity free vacancy diffusion[11-13] and ion implantation enhanced interdiffusion[5-8] have been reported to enhance the interdiffusion. All these techniques are spatially selective, permitting intermixing enhancement only in the regions requiring a larger bandgap, leaving other regions unmodified. In addition, they use standard QW structures and require no special growth processes. In this study we have used ion implantation to create defects in regions of the wafer that we wish to modify.

One of the major requirements for any technique used to control the bandgap energy is that it must not result in a degradation of the optical or electrical properties of the device. We will demonstrate that the process described in this paper permits good spatial control of the bandgap without any serious performance penalties.

2. EXPERIMENTAL METHODS

The layer structure of the device studied here is shown schematically in Figure 2. Basically, it is an unstrained InGaAs/InGaAsP/InP laser heterostructure containing an active region (five $In_{0.53}Ga_{0.47}As$ QWs with $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$ barriers) clad with InP. From the surface the layers are: 0.2 μm Zn-doped (1×10^{19} cm^{-3}) $In_{0.53}Ga_{0.47}As$ cap, 1.5 μm Zn-doped (5×10^{17} cm^{-3}) InP, 0.05 μm undoped $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$, five repeats of (0.02 μm undoped $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$, 6.0 nm undoped $In_{0.53}Ga_{0.47}As$), 0.07 μm undoped $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$, 1.0 μm S-doped ($1\times10^{18}$ cm^{-3}) InP on a S-doped (5×10^{18} cm^{-3}) InP substrate.

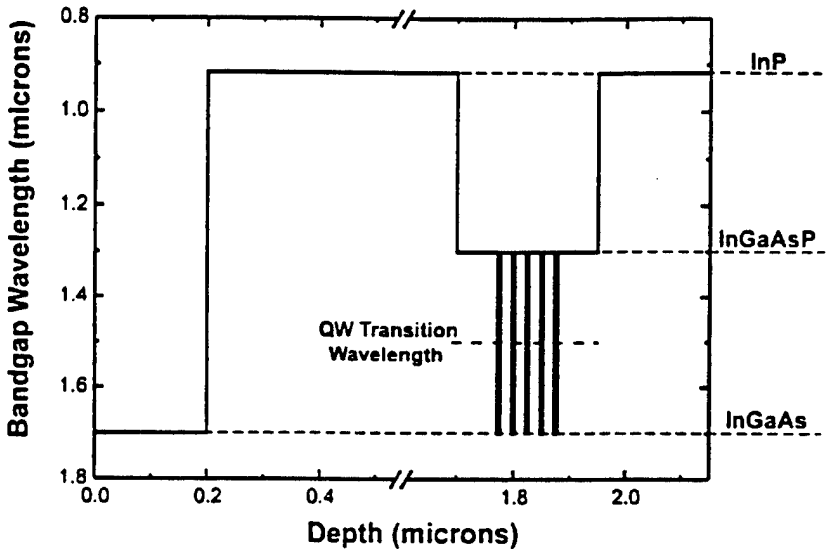

Figure 2: Schematic diagram illustrating cross-section of InGaAs/InGaAsP QW laser structure studied in this paper.

Ion implantation was accomplished with the 1.7 MV Tandetron accelerator at the University of Western Ontario. Phosphorus was chosen as the ion species to avoid adding dopant to the structure. A constant particle flux of 6.6 nA/cm^2 was used to implant a dose of 2.5×10^{13} phosphorus ions/cm^2 for each implantation energy at a fixed substrate temperature of 200 °C. To minimize ion channeling, during implantation the samples were tilted so that the ions were incident at an angle of 7° to the surface normal.

After implantation the samples were annealed at 700 °C for 90 seconds in a nitrogen atmosphere, using an AG associates Heatpulse 410 rapid thermal annealer (RTA). These conditions were found to produce large intermixing of the QWs in the implanted regions of the samples without causing significant intermixing in the unimplanted regions. During the RTA process, QW intermixing occurs in the implanted regions provided sufficient defects are available to permit enhanced interchange of atomic species across the QW/barrier material interfaces. In the case of InGaAs/InGaAsP QWs, both group III and group V elements may exchange in principle (although the process may be modified if the diffusion rate of one of these groups is much larger than the other). This can lead to either a blue shift or a red shift in the bandgap energy. In our case we always observed blue shifts which indicates that diffusion of the group V element is of critical importance in this system. The annealing also has the additional effect of removing the damage sites created in the lattice during implantation.

We used the position of low temperature (4.2 K) photoluminescence (PL) peak energy from the InGaAs QWs to monitor the modification of the QW shape. PL was excited using a titanium-sapphire laser tuned below the InP bandgap energy. The emission spectra were analyzed with a Fourier transform infrared interferometer employing a thermoelectrically cooled InGaAs detector. The resolution was better

than 0.5 meV. Waveguide absorption measurements, to study the effects of implantation and annealing on the bandedge energy and propagation losses, were made at room temperature with tunable laser diode as a light source. Using a polarization maintaining, tapered fibre, light was butt-coupled to a single mode ridge waveguide cavity made from the implanted and unimplanted laser material and then coupled out and monitored with a photodetector. The measured contrast of the Fabry-Perot fringe pattern was analyzed to yield waveguide loss as a function of wavelength from 1.46 to 1.59 μm. To investigate the lasing performance of the structure after processing, the material was patterned into broad area lasers, and the lasing spectra and threshold currents were measured.

3. RESULTS

In Figure 3 (a) we present normalized PL spectral peaks of InGaAs QWs obtained from the as-grown samples and samples subjected to ion implantation and 90 second RTA. The InGaAs QW peak

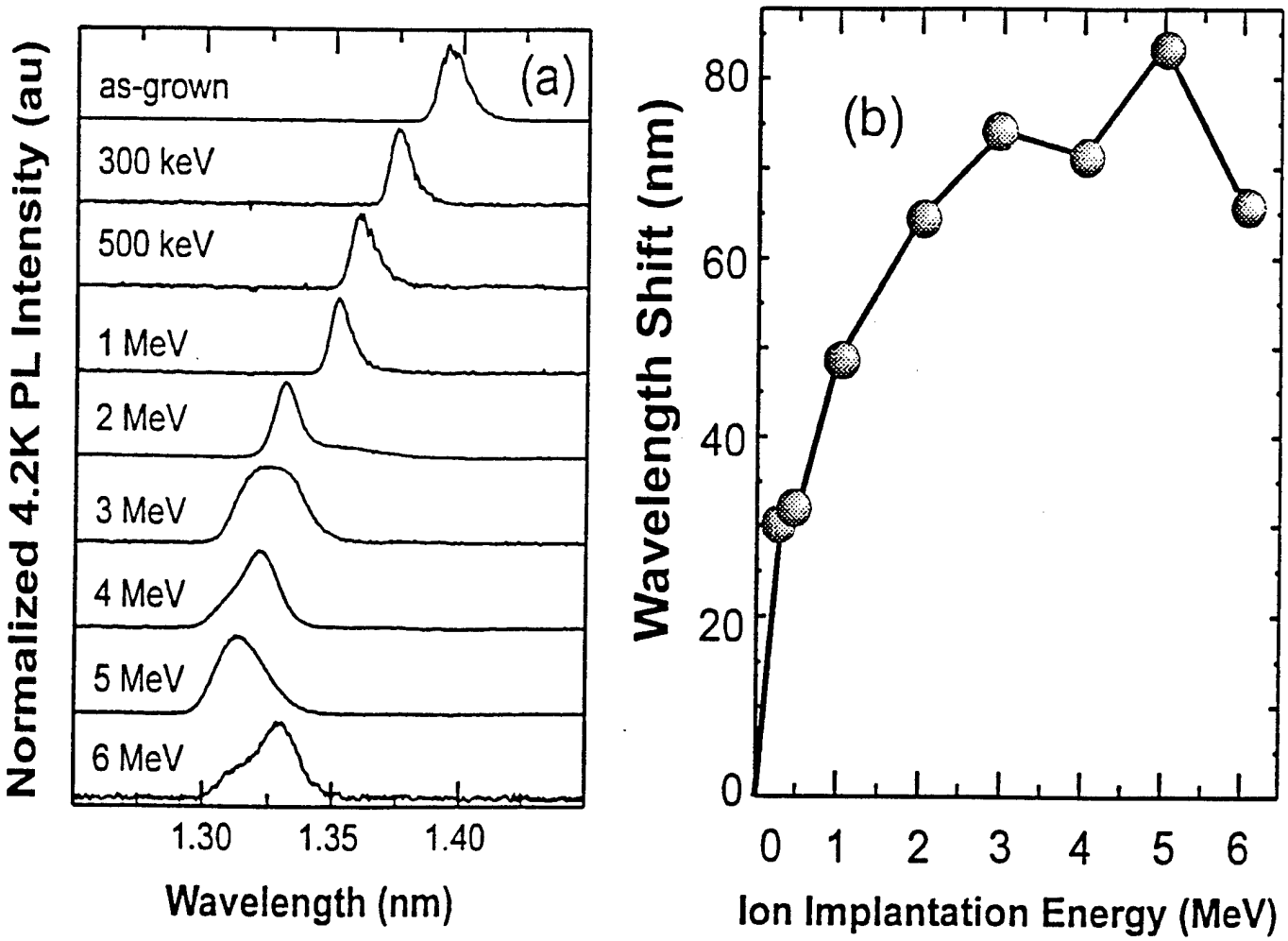

Figure 3: (a) 4.2K PL spectra of InGaAs/InGaAsP QWs for various ion implantation energies (P^+ ions, dose = 2.5 x 10^{13} cm^{-2}). The bottom four spectra were multiplied by about an order of magnitude.; (b) wavelength blue shift from Figure 3(a) as a function of ion implantation energy.

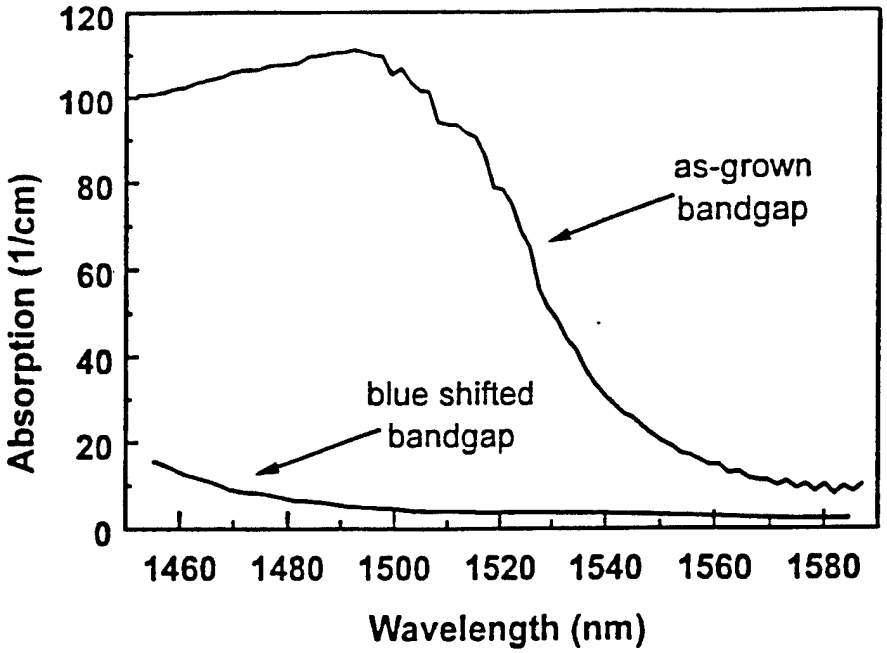

Figure 4: Waveguide absorption spectra of as-grown and bandgap shifted InGaAs/InGaAsP QWs.

energy increases dramatically as a function of ion energy, with significant intermixing occurring at very low implantation energies, such that the implanted ions do not reach the active QW region. This is a consequence of the large mobility of defects during the annealing process.[6] Close to the maximum shift is obtained with ions having as little as 2 MeV energy, i.e. with projected ranges well short of the QWs. Up to this ion energy the linewidth is comparable to that of the as-grown material, and there is no reduction in peak intensity, suggesting that the resulting intermixed QWs are still of very high optical quality. At ion energies of 3 MeV and higher, the spectra appear significantly different, the peaks broaden and the intensity drops. With an energy of 3 MeV, implanted ions reach the QWs, resulting in damage which cannot be removed by the annealing process. This would result in a degradation of device performance. Therefore, only samples implanted with ion energies less than 3 MeV were used for device testing. Figure 3 (b) presents the PL peak energy shift as a function of ion energy, demonstrating that significant control over the energy shifts is possible even using ions with energies less than 3 MeV.

In order to investigate the effect of this procedure on waveguide quality, we performed waveguide loss measurements using the Fabry-Perot fringe technique. Four micron wide ridge waveguides were fabricated on both as-grown and implanted (at an ion energy of 2 MeV) material. The sample was cleaved to form a 1 mm long Fabry-Perot cavity between the facets. A tunable diode laser was used as a light source and coupled into the TE mode of the waveguide through a polarization-maintaining tapered fibre. A similar fibre was employed at the other end of the waveguide to collect the transmitted light. Figure 4 illustrates the absorption constant of the implanted and as-grown waveguides as a function of wavelength. The bandgap of the implanted waveguides has been blue-shifted 90 nm with respect to the as-grown waveguide. The actual bandgap cannot be observed since it is beyond the range of the tunable source. At the bandedge of the as-grown material (~1.5 μm), the absorption constant is reduced from 110 cm^{-1} to 4 cm^{-1}. This absorption value also includes excess losses such as the scattering loss resulting from imperfections of the ridge waveguide. It is worth noting that the loss below the bandedge for the implanted material appears to be even lower than for the as-grown material below the bandedge, again indicating the high optical quality of the intermixed material. The absorption observed in Figure 4 may be

limited by intervalence band absorption processes in the p-type InP cladding layer[16] rather than related to the effects of intermixing the QWs.

As described so far, the process permits the creation of two regions with different bandgap energies on a single laser wafer, the as-grown region and the implanted region. For PICs with more elaborate functionalities (e.g., optical switches, optical add&drops, etc.) more flexibility is required, since the number of different bandgap energies needed on a single wafer would be larger than two. There are a number of techniques for acquiring flexibility by using bandgap energy control through ion implantation. The simplest are 1) adjusting the total ion dose, and 2) regulating the ion energy (as shown in Figure 3 (b)). Both can be accomplished through repetitive masking and implanting of the sample until all of the different regions receive their required dose/ion energy. But this is a tedious process since it requires many steps and mask alignments. An alternative technique is to control the ion energy (and thus defect dose) in different regions of the sample with a single, somewhat more elaborate, mask and a single implantation step. For example, a semi-transparent mask that slows ions down but does not stop them completely, as shown schematically in Figure 5, can be utilized. In this case a SiO_2 mask with different thicknesses (0, 0.65, 1.2 and 2.2 μm) was evaporated on the sample surface so that the thickest region stopped the ions completely (the ion energy in this case was 1 MeV). The thinner regions slowed down the ions by different amounts, resulting in different total effective defect doses, and thus different bandgap

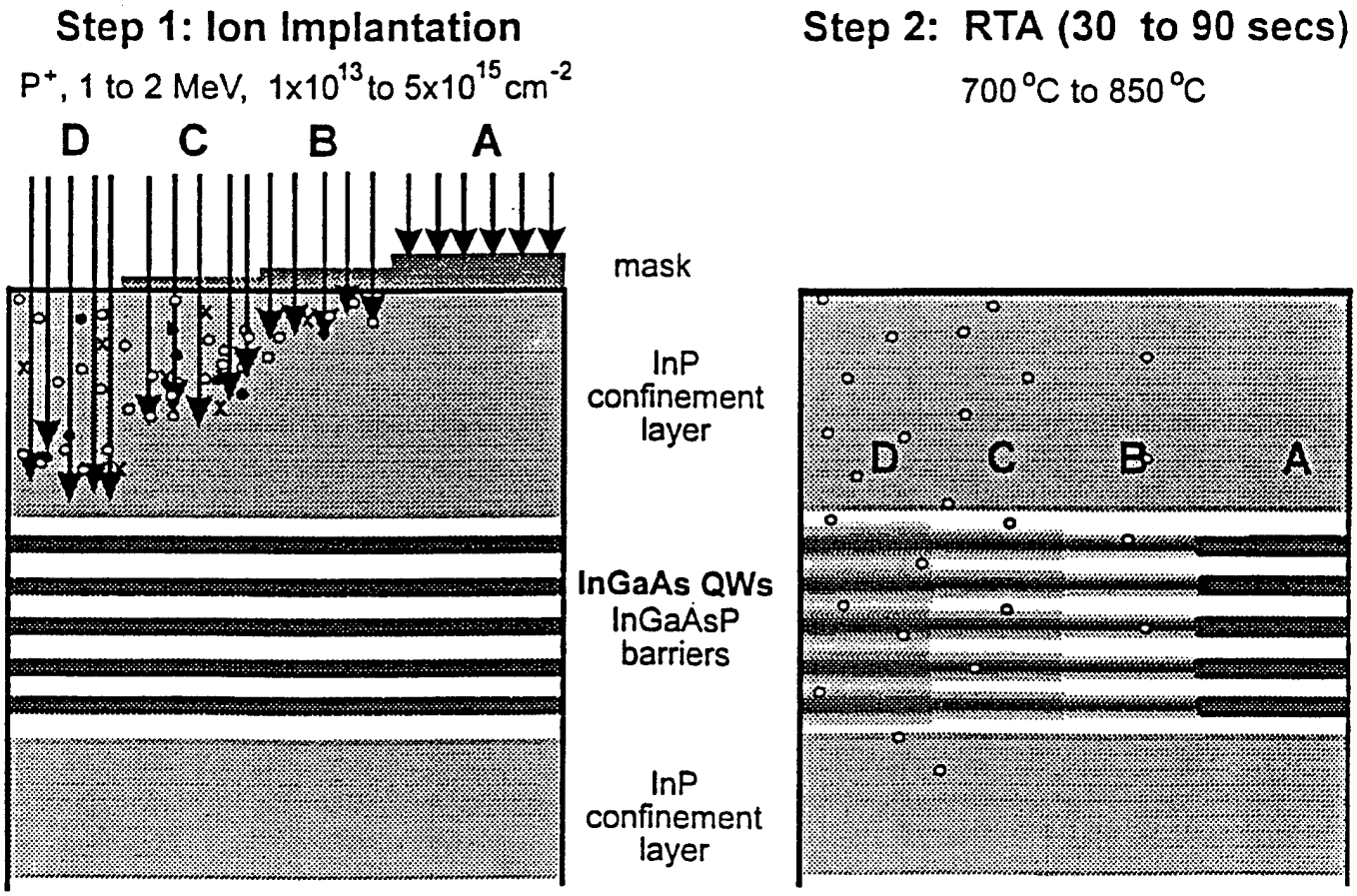

Figure 5: Two step process for achieving four different bandgap energies on a single wafer using a variable thickness mask and a single ion implantation.

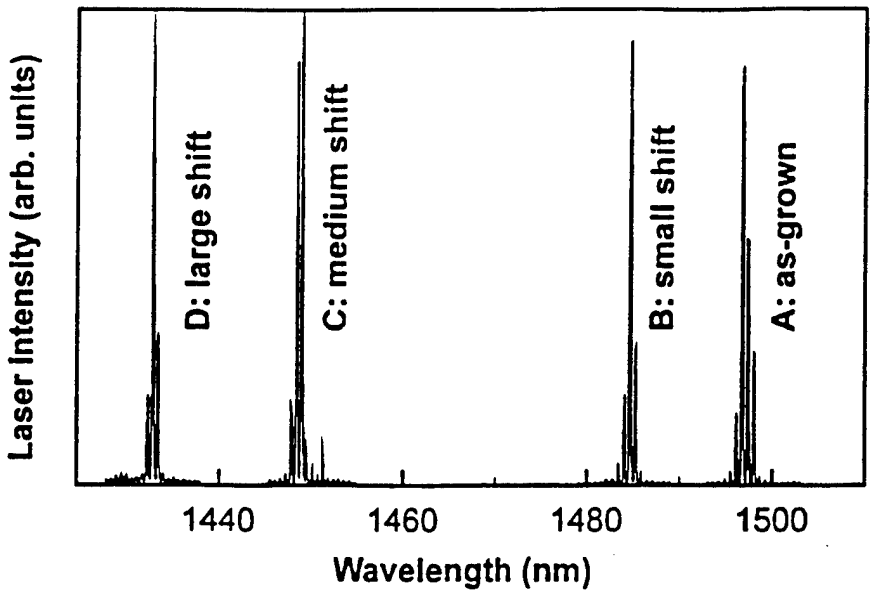

Figure 6: Bandgap shifted laser diode emission spectra. These lasers were from the same wafer and shifted different amounts using the technique described in Figure 5.

shifts for four different regions. The SiO_2 layer was removed before the sample was annealed.

The regions under the four different thicknesses of mask were processed into broad area lasers with stripe widths of 60 μm and cavity lengths of 500 μm. They were tested at room temperature under pulsed conditions (1 μs pulses at a repetition rate of 1 kHz). Figure 6 presents the lasing spectra from the four regions, fabricated from one sample, which have undergone different degrees of intermixing, and shows a wavelength spread of 64 nm. The threshold current measured from the bandgap shifted lasers was essentially constant, ~410 mA. This was the same value obtained from laser structures fabricated from the as-grown wafer. This indicates the high quality of the shifted laser material, as any damage left in the active region of the device after implantation and annealing would add to the loss in the cavity and increase the threshold current.

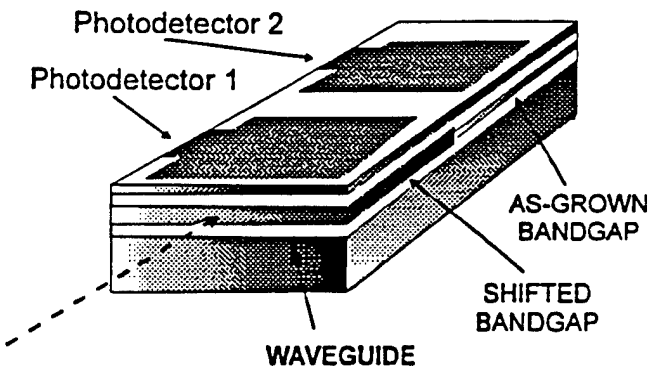

Figure 7: Schematic diagram illustrating operation of two wavelength WDM DEMUX fabricated using QW intermixing.

Since this technique is simple to implement, and results in material of very high optical quality, many novel PICs can be envisioned. For example an extremely simple two wavelength demultiplexer is shown in Figure 7. It consists of two regions of a standard laser structure, one of which has been intermixed and one that has not. Light is coupled into the waveguide and passes through the intermixed into the non-intermixed region. Photons with a wavelength shorter than the bandgap of the blue shifted section will be absorbed in that region, resulting in a

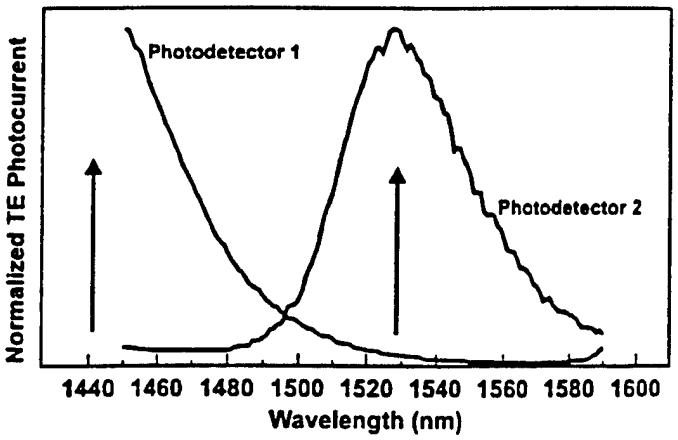

Figure 8: Normalized room temperature TE photocurrent spectra of as-grown and intermixed regions of two wavelength WDM demultiplexer.

photocurrent which is monitored by an electrical contact to that section. Longer wavelength light that is not absorbed in the first section will pass through to the as-grown region which has a smaller bandgap energy, and will be absorbed and detected there. Figure 8 presents the photocurrent spectra observed in each of the two regions as light from a tunable laser is scanned from 1.45 μm to 1.59 μm and sent into the intermixed end of the structure. This device is extremely easy to fabricate and is able to independently detect signals at two different wavelengths (say, at the values indicated by the arrows. Note that this device has not been optimized for efficiency or crosstalk.).

4. CONCLUSIONS

We have demonstrated a simple technique that permits spatial control of the quantum well bandgap of a 1.55 μm laser structure without serious degradation of device performance. This process is easy to implement and should simplify the creation of complex photonic integrated circuits.

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Sylvain Charbonneau was born in Montreal in 1961. He completed his B.Sc. and M.Sc. degrees in Physics at the University of Ottawa in 1983 and 1985, respectively. He then received his Ph.D. degree in Solid State Physics from Simon Fraser University in 1988 under the direction of Mike Thewalt. Both his Master and Ph.D. focussed on the optical properties of semiconducting compounds (GaAs, ZnSe), i.e., Photoluminescence (PL), PL excitation, Time-resolved PL, Photoconductivity, PV and absoption spectroscopy.

Dr. Charbonneau spent a 1 year Post-Doc in the Division of Physics of the NRC and became a Research Officer in 1989. Since his arrival at the NRC, Dr. Charbonneau has focused his research on the study of optical properties of semiconducting compounds (group III-V and IV) in bulk (3D), quantum wells (2D), quantum wires (1D) and quantum dots (0D) structures. He has been involved in the field of Quantum Well Intermixing for the past five years where he has published a number of papers and obtained 3 patents on the applicaion of this technique in the field of optoelectronic integration (WDM) in InP based materials. He is an Adjunct Professor in the Physics Dept. at the University of Ottawa as well as in the Dept. of Engineering Physics at McMaster University.

Status of Science and Technology in Chile and Opportunities for International Collaboration

Dr. Eduardo Saravia, Comision Chilena de Energia Nuclear

Chile's economy has been growing consistently marking the twelfth straight year of growth, with an average expansion of 6.3% a year. All predictions indicate that the country will continue to grow at this rate for the next five years. Chile's unemployment is under 5% and the investment rate has reached 28% of the country's GDP. However, in spite of this remarkable macroeconomic situation, there is still a major task to be accomplished in terms of modernization of the public sector and to incorporate innovation to the industrial sector as a way of living. It is well known that there exists a strong correlation between the amount of resources that a country spends on R&D and the degree of its social and economic development. In this sense, the percentage of the GDP spent on R&D by countries with an intermediate level of development, such as Australia, Canada and several European countries are close to 1.5-1.7% level. In Chile in the past four years the expenditure on R&D increased from 0.5% to a 0.8% of the GDP as a result of significant efforts made by Government and private institutions in fostering research and development. For this purpose, various national programs (e.g., FONDECYT, FONDEF, and FONTEC) have been created in recent years tailored specifically to foster the scientific and technological development and to increase Chile's competitiveness in key areas of the country. The Comision Nacional de Investigacion Cientifica y Tecnologica (CONICYT) and the Corporacion de Fomento a la Produccion (CORFO) are the governing bodies of these national funds. Although the international cooperation has played a major role in the development of Chilean science and technology since the early fifties, generally these activities have not been a result of formal and official engagement and planning among institutions at the national level, but rather due to personal initiatives of scientists. It is essential to develop mechanisms to facilitate the interaction and the collaborative R&D work on solid and permanent basis among scientists in the international community. Particularly, Chile welcomes the initiative to promote strong interactions among the Pan American Countries represented in this Workshop.

Status of Science & Technology in Chile

Opportunities for International Collaboration

by

Dr. Eduardo Saravia

CCHEN-CHILE

CHILEAN ECONOMY

Chile's economy has been growing consistenly with an average growth rate of 6.3% in the past 12 years.

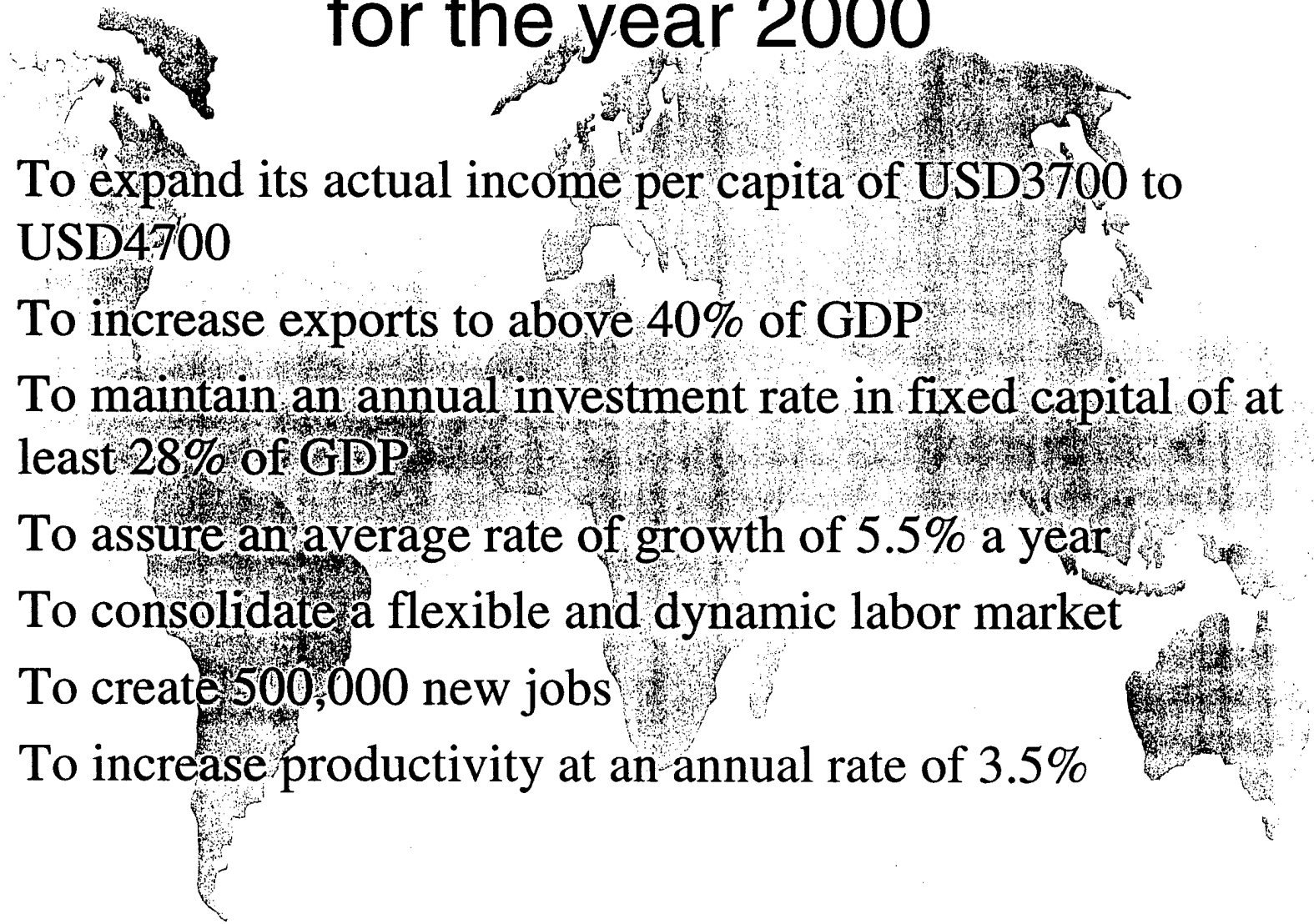
All predictions indicate that the country will continue to grow at this rate for the next five years. Chile's underemployment is under 5% and the investment rate has reached 28% of the country's Gross Domestic Product (GDP).

Chile is entering a phase of mature economic development, with high rate of use of resources.

However, the policy of continuing the exports of low added products could mean Chile could lose its competitiveness.

This must force a gradual but decisive transformation of Chilean economy towards activities which imply a greater use of capital and the offering products with greater value added.

CHILE's Economic Goals for the year 2000



To expand its actual income per capita of USD3700 to USD4700

To increase exports to above 40% of GDP

To maintain an annual investment rate in fixed capital of at least 28% of GDP

To assure an average rate of growth of 5.5% a year

To consolidate a flexible and dynamic labor market

To create 500,000 new jobs

To increase productivity at an annual rate of 3.5%

The Chilean Program on Science & Technology

Investment on S&T: In 1989 it was of 0.53% of the GDP and it reached 0.8% in 1994.

Low investment of the private sector on R&D: 1% of their sells compared to 4.5% average world level.

The productive sector spends <12% in R&D and uses only 6% of scientists. In industrialized countries this number is close to 45% in both cases.

The Government's S&T Program was initiated in 1982 and it is a unique experience in Chile.

Chilean Program... (Cont.)

The Instruments within this Program are complementary to each other, and they seek three main objectives:

To foster the R&D at Chilean institutions.

To commit these institutions to the innovation process.

To utilize and consolidate the capacities on S&T at research institutions to link them to industries to improve the country's competitiveness.

Three of the most effective instruments of this National Program are: FONDECYT, FONDEF and FONTEC.

Key Institutions Fostering S&T

The National Commission for Scientific and Technological Research, CONICYT is a Government Agency created in 1967 to assist and advise the President of Chile on S&T policies and other matters. CONICYT current objectives are: To define science and technology policies at the national level; to evaluate the national science and technology system; to support the development of human resources; to finance R&D programs and projects; to manage bilateral and multilateral international cooperation agreements; to disseminate scientific and technological knowledge and; to promote the use of scientific and technological information systems.

Key Institutions... (Cont.)

The Agency for Fostering Industrial Development, CORFO is a Goverment Institution created in early fourties which has played a fundamental role in the Chilean's economic development over the decades. CORFO has two important instruments:

The national Technology and Productivity Development Fund (FONTEC) which aims to stimulate innovation at the corporative level.

CORFO's Technological Institute Affiliated System (SIT) operating under its direction. These institutes are the Natural Resources Research Center (CIREN), The Fishing Development Institute (IFOP), the Forestry Institute (INFOR), Chile's Bureau of Standards (INN), and the technological Research Institute (INTEC).

FONDECYT

Fondo Nacional de Desarrollo Cientifico y Tecnologico (National Fund for Scientific and Technological Development)

Created in 1982 to fund high-quality research projects in all disciplines. Funded projects may last from one to three years.

Once a year researchers submit research proposals. FONDECYT's Superior Councils of S&T Development approve funding.

Budget for 1992-1995 was of USD 60 millions.

FONDEF

Fondo de Fomento al Desarrollo Cientifico y Tecnologico (Natuional Fund for Fostering Scientific and Technological Development)

Its was created in 1991 to finance joint projects between the scientists and productive sectors, aiming to increase Chile's competitivenes in areas key to its development.

These joint efforts facilitate the diffusion of research results and in doing so achieve expected economic and social benefits.

Funding is available in six areas where Chile enjoys comparative adavantage: Agriculture, Fishery and Aquaculture, Forestry, Information Technology and Mining.

FONDEF (Cont.)

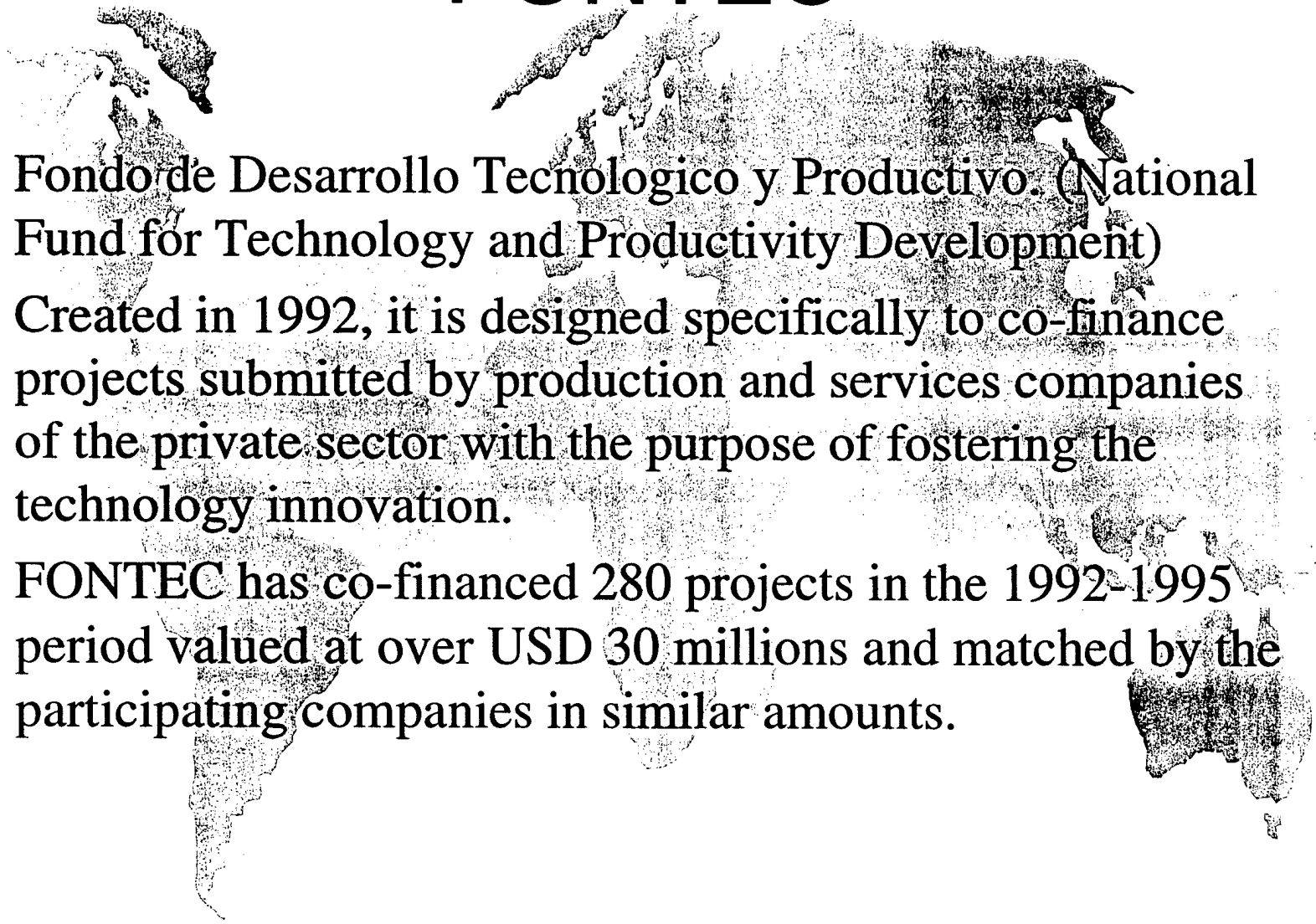
Projects must include the participation of industry to guarantee the transfer of results and know-how. 18% of the project total cost must come from this sector.

The expected Internal Rate of Return (IRR) for a project must not be less than 12% to qualify.

Funds are awarded through open competition. Both public and private, non-profit, R&D institutions may submit proposals.

Funding for 1992-1995 period was of USD 65 millions.

FONTEC

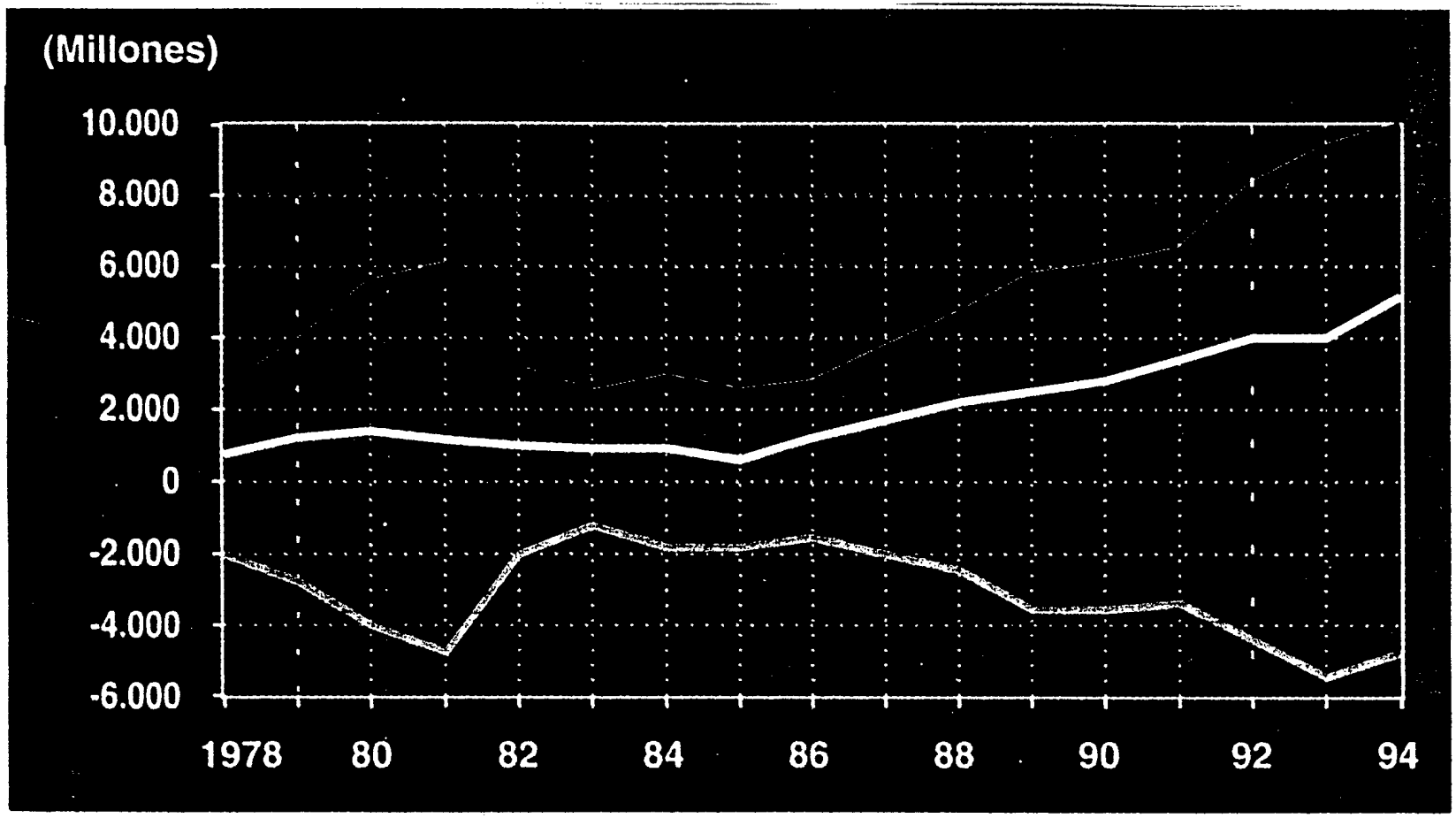


Fondo de Desarrollo Tecnologico y Productivo. (National Fund for Technology and Productivity Development)

Created in 1992, it is designed specifically to co-finance projects submitted by production and services companies of the private sector with the purpose of fostering the technology innovation.

FONTEC has co-financed 280 projects in the 1992-1995 period valued at over USD 30 millions and matched by the participating companies in similar amounts.

Industrial Trade Balance (in Millions of US Dollars)

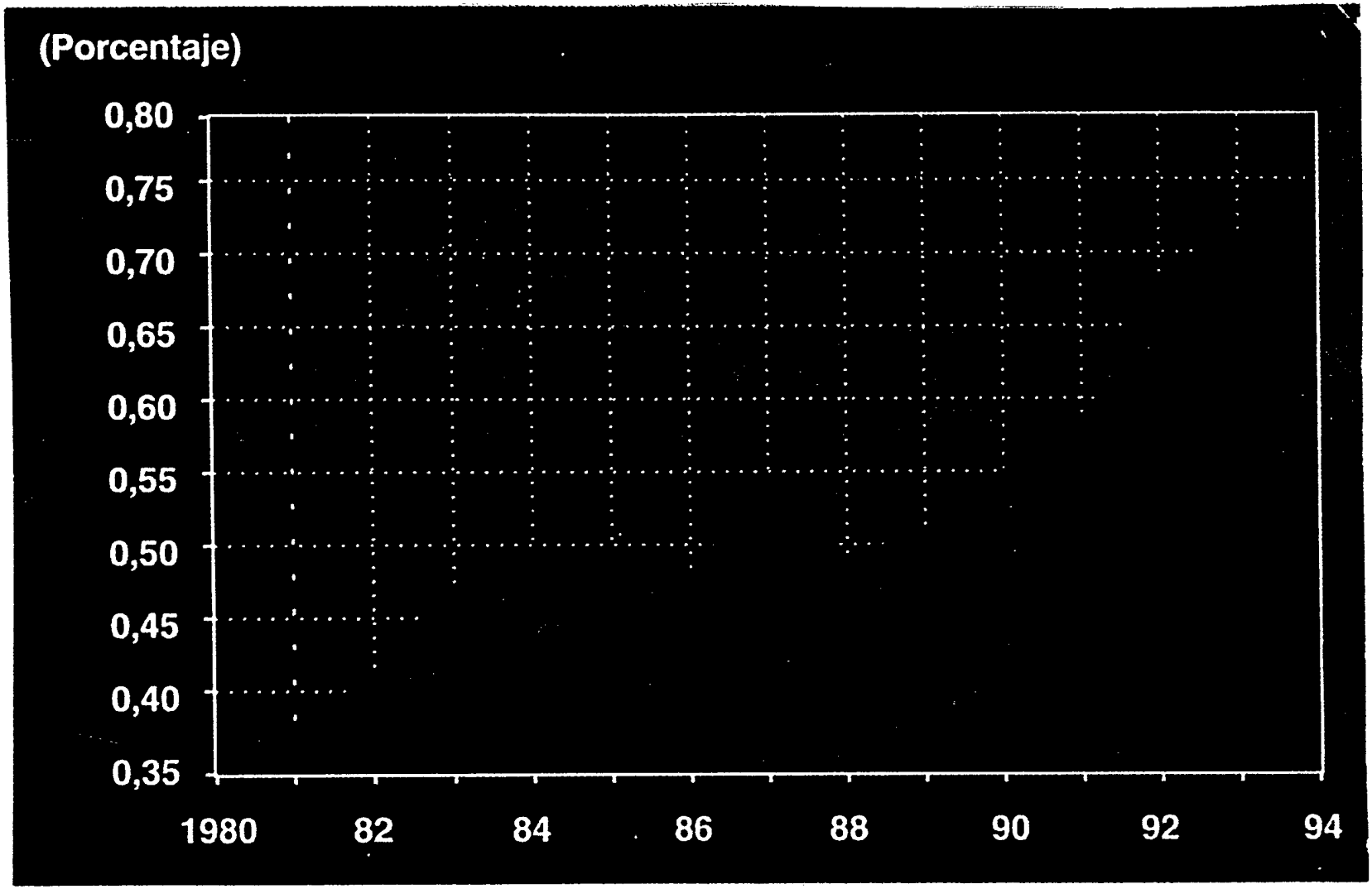


SOURCE: Central Bank of Chile.

Red: Imports
Yellow: Exports
Green: Balance

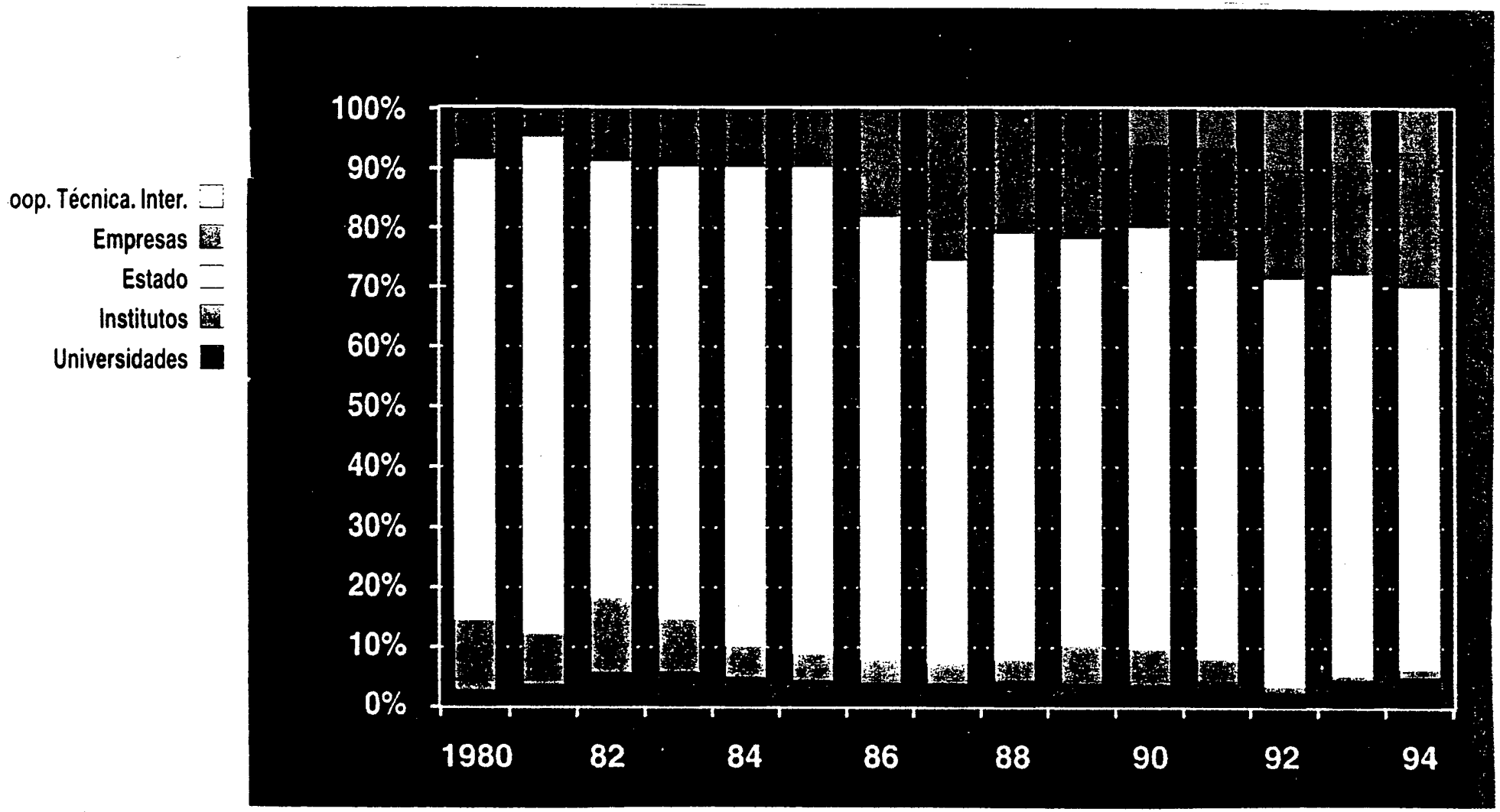
- Imports
- Exports
- Balance

Percentage of the GDP Spent on R&D



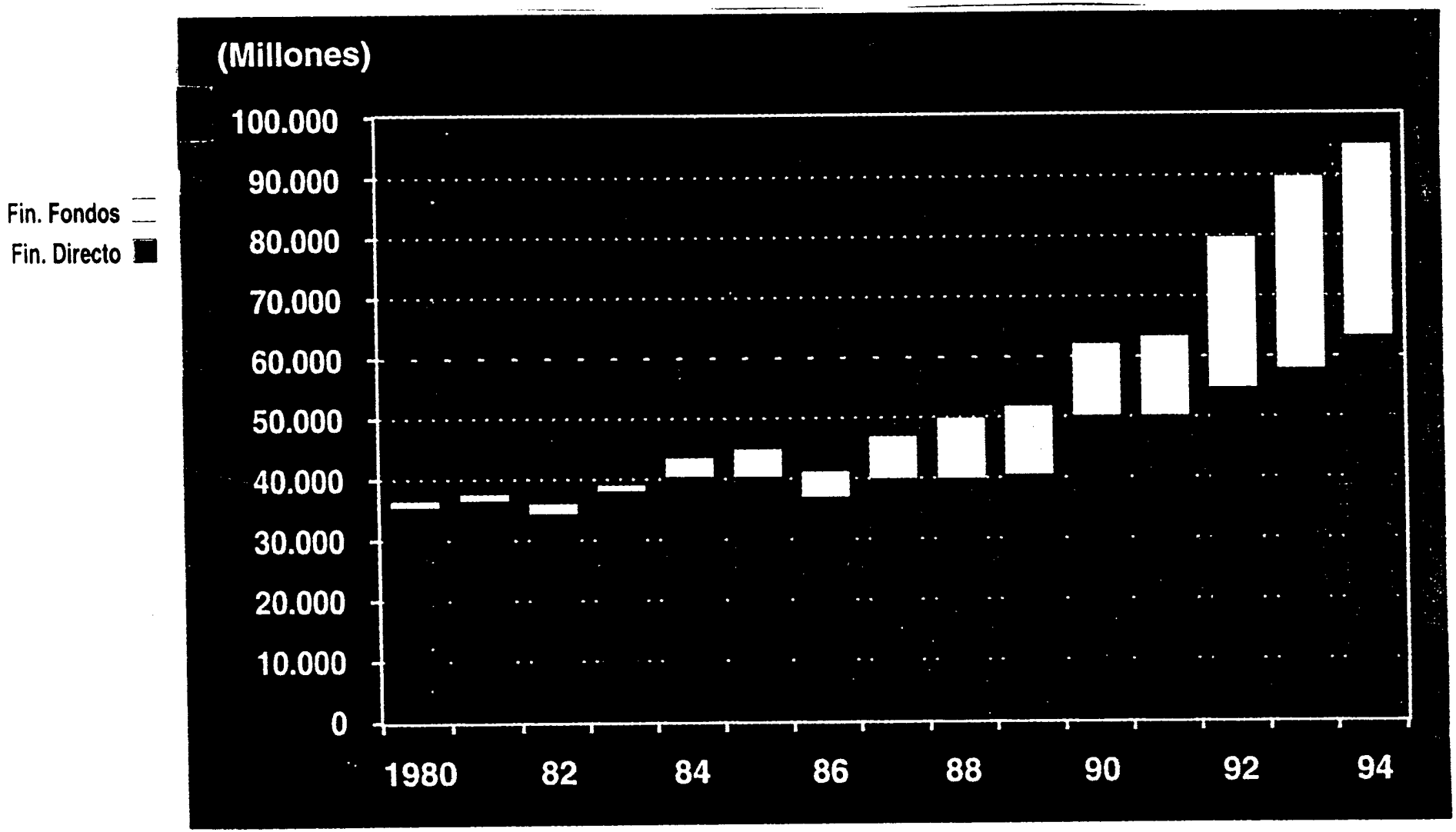
SOURCE: Information Department of CONICYT, Chile

Financial Resources for the National R&D



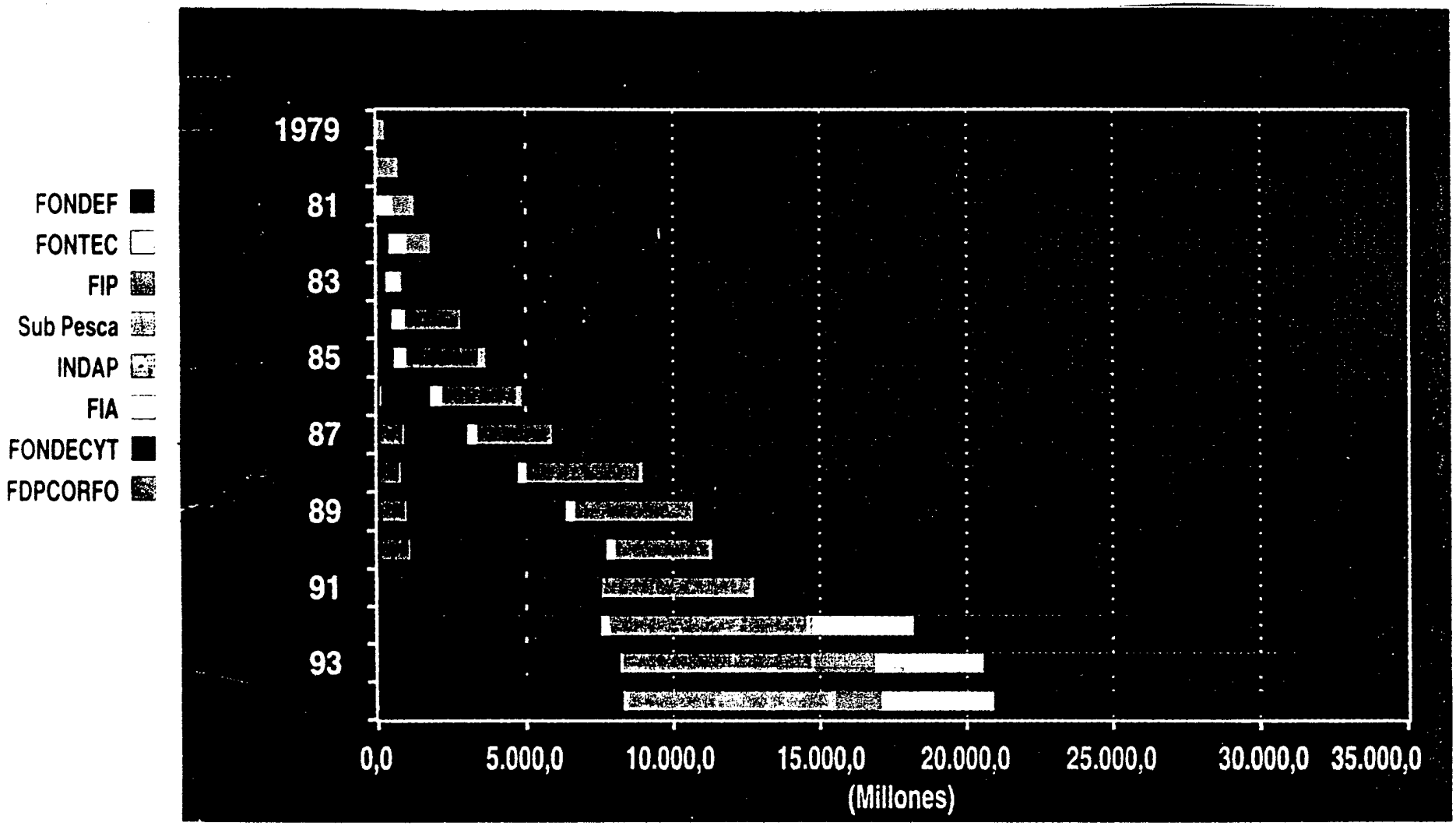
SOURCE: Information Department of CONICYT, Chile.

Government Support of R & D:
Direct Financing and via Competitive Funds



SOURCE: Information Department of CONICYT, Chile.

Evolution of Government Competitive Funds



SOURCE: Information Department of CONICYT, Chile.

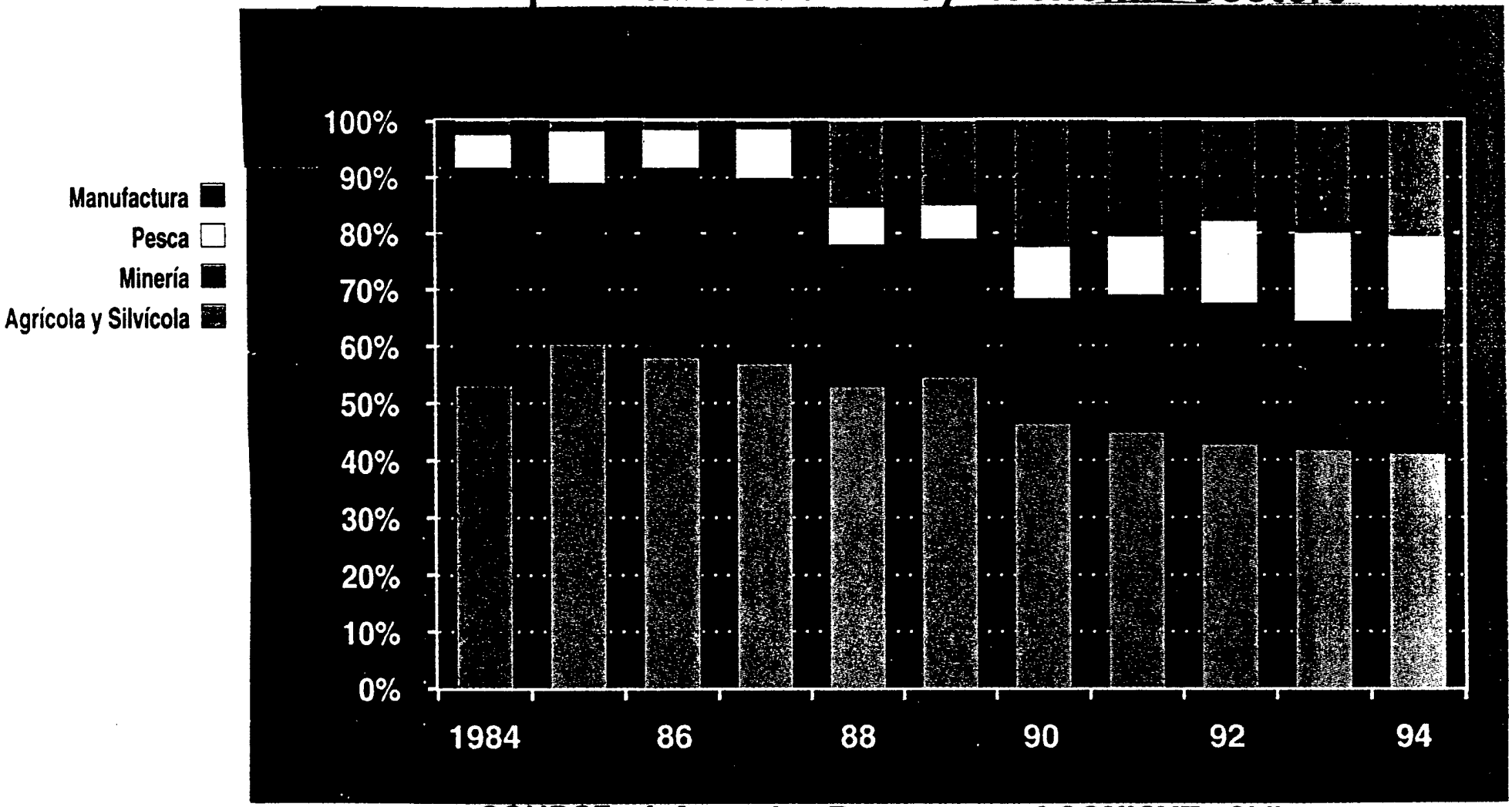
Expenditure on R&D per Inhabitant

	Gasto nacional en I&D			Gasto en I&D por habitante	
Años	Millones de Pesos 1994	Millones de US$ de cada año	Millones de habitantes	$ p / hab.	US$ p / hab.
1980	47.088,6	107,58	11,0	4.281,5	9,8
81	45.291,4	123,86	11,2	4.057,0	11,1
82	47.290,7	108,91	11,3	4.174,0	9,6
83	50.809,5	96,20	11,5	4.410,6	8,4
84	54.687,2	99,30	11,7	4.670,1	8,5
85	55.173,0	80,16	11,9	4.636,3	6,7
86	55.978,3	81,02	12,1	4.630,0	6,7
87	68.663,7	104,76	12,5	5.477,1	8,4
88	69.148,5	108,35	12,7	5.424,2	8,5
89	77.842,3	131,01	13,0	6.005,9	10,1
90	87.202,4	161,95	13,2	6.619,6	12,3
91	92.844,7	183,34	13,4	6.936,1	13,7
92	*118.251,1*	*259,61*	13,6	*8.695,3*	*19,1*
93	*131.972,5*	*293,00*	13,8	*9.554,1*	*21,2*
94	*145.382,2*	*346,00*	14,0	*10.365,1*	*24,7*

Nota: en itálica cifras provisionales

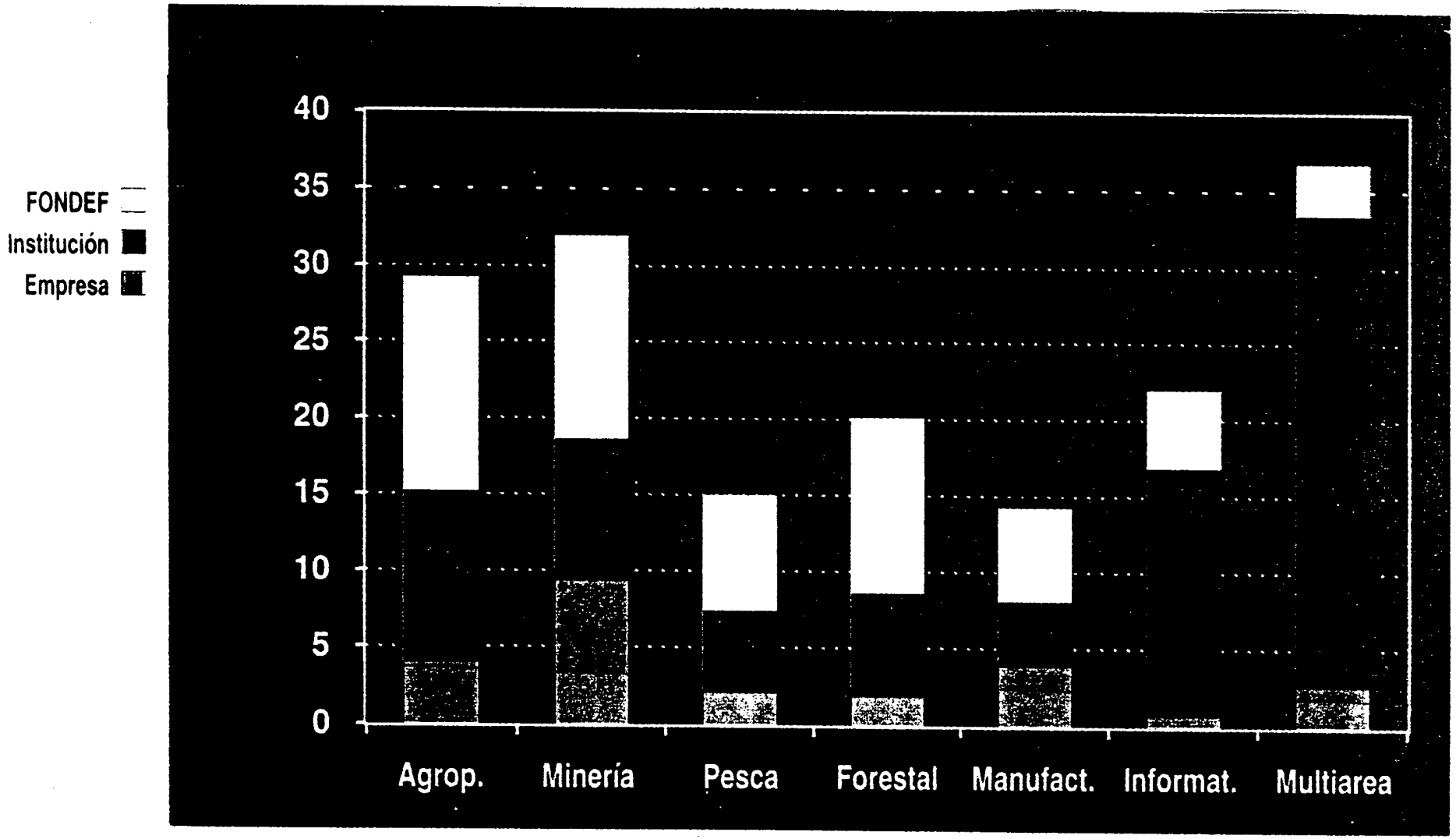
SOURCE: Information Department of CONICYT, Chile.

Expenditure on R&D by Economic Sectors



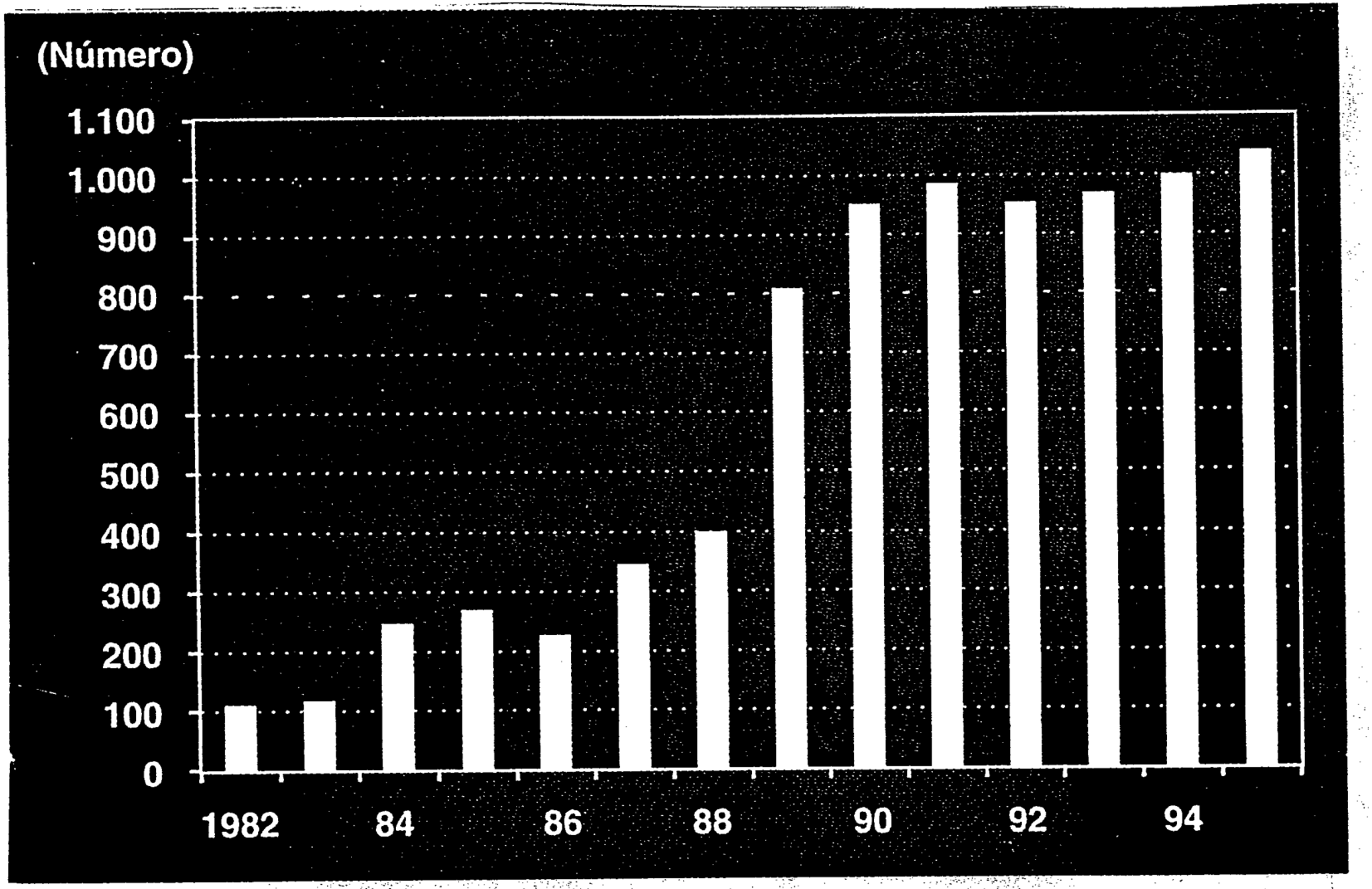
SOURCE: Information Department of CONICYT, Chile.

FONDEF- 1st and 2nd Competitive Solicitations Distributions of Resources for the Prioritized Areas (in Millions of US Dollars of July 1993)



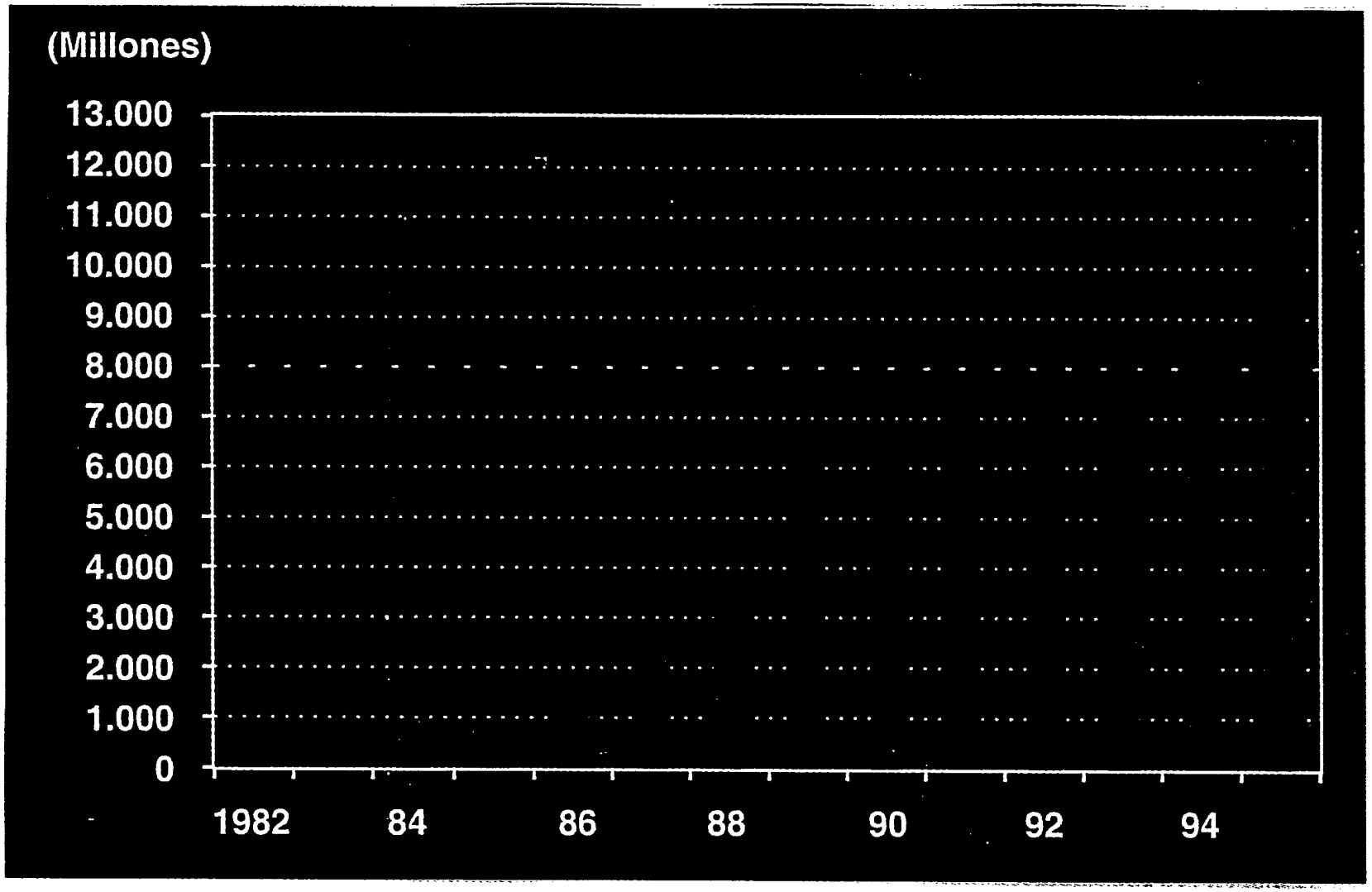
SOURCE: FONDEF-CONICYT, Chile.

Number of Current FONDECYT Projects



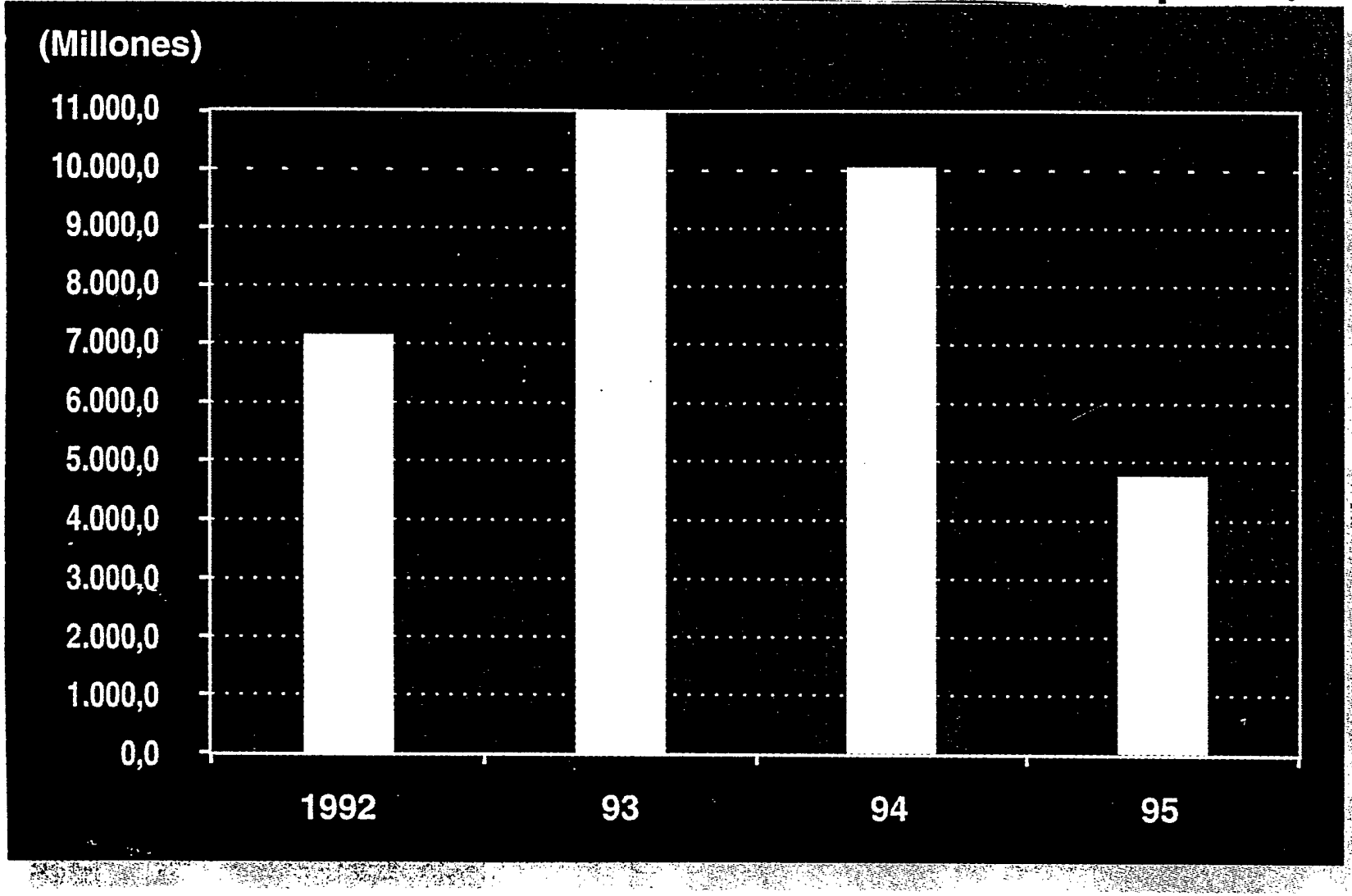
SOURCE: Department Projects, CONICYT, Chile.

Evolution of the Budget for FONDECYT (in millions of pesos)



SOURCE: Department of Projects, CONICYT, Chile.

Evolution of the Budget for FONDEF (in millions of pesos)



SOURCE: FONDEF-CONICYT, Chile.

Number of Researchers in the R&D System with Graduate Degree

3 - 3

Años	Universidades	Institutos	Empresas	Total Postgraduados	Total Investigadores
1981	2.239	75	s/i	2.314	3.620
82	2.325	83	s/i	2.408	3.747
83	2.633	85	s/i	2.718	3.921
84	2.793	91	s/i	2.884	4.078
85	3.111	102	s/i	3.213	4.269
86	3.440	111	s/i	3.551	4.439
87	3.541	126	s/i	3.667	4.773
88	3.702	131	16	3.849	4.986
89	3.833	137	19	3.989	5.296
90	3.870	147	s/i	4.017	5.538
91	3.855	154	s/i	4.009	5.721
92	3.918	177	s/i	4.095	5.926
93	3.979	192	s/i	4.171	6.175
94	4.031	196	s/i	4.227	6.429

SOURCE: Data Base of Universities and CONICYT, Chile.

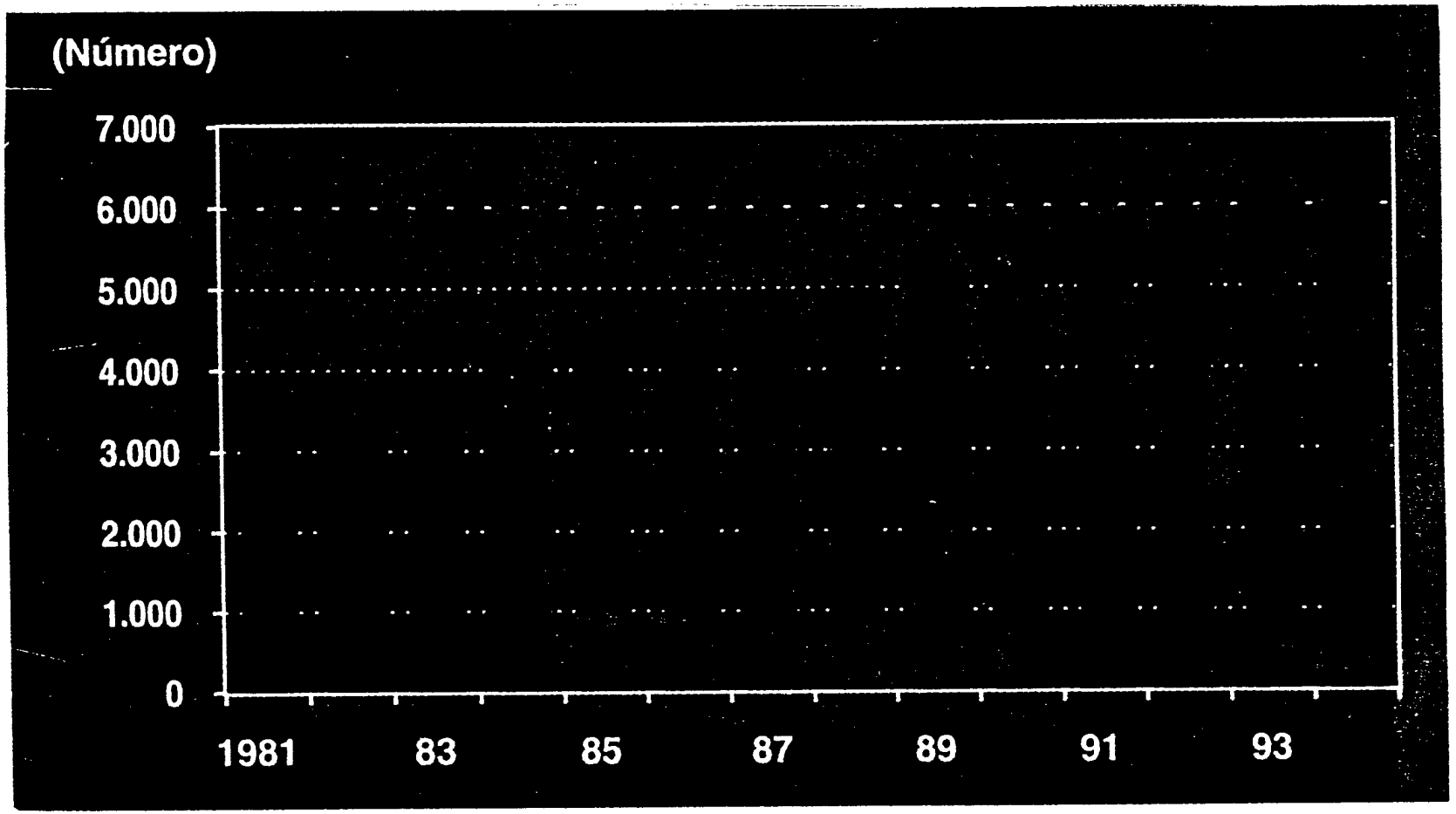
Total Number of Researchers per Institutional Sector

Años	Universidades	Institutos	Empresas	Otros
1981	2.634	799	s/i	187
82	2.761	797	s/i	189
83	2.871	820	s/i	230
84	2.981	837	30	230
85	3.114	877	50	228
86	3.244	891	75	229
87	3.354	900	200	319
88	3.462	961	334	229
89	3.570	1.084	314	*328*
90	3.686	1.080	386	*386*
91	3.803	1.098	456	364
92	3.942	1.116	*526*	342
93	4.045	1.207	*596*	*327*
94	4.178	1.258	*666*	*327*

Nota: los datos en itálica están estimados.

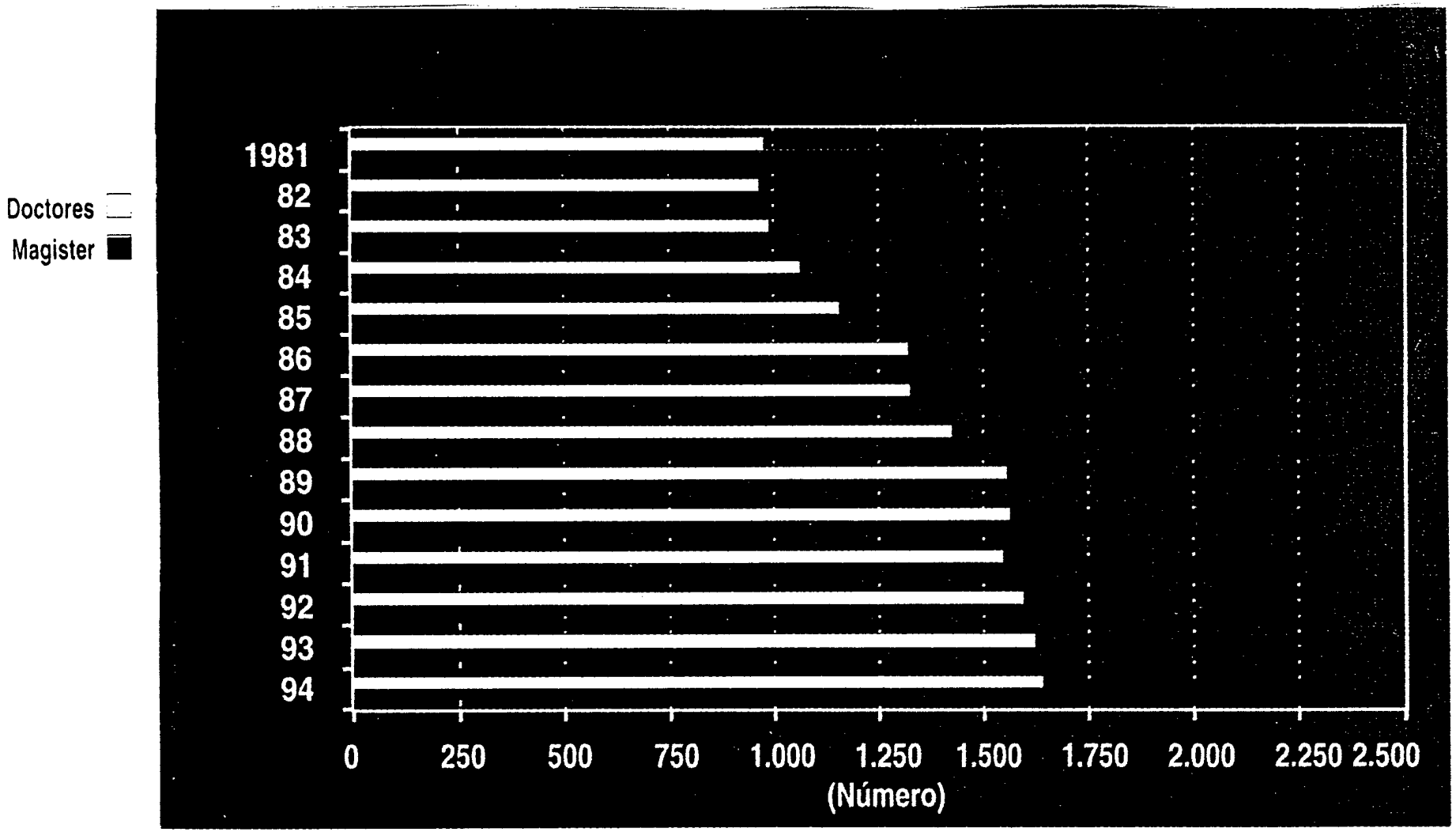
SOURCE: Data Base of Universities and CONICYT, Chile.

Total number of Scientists and Enginners



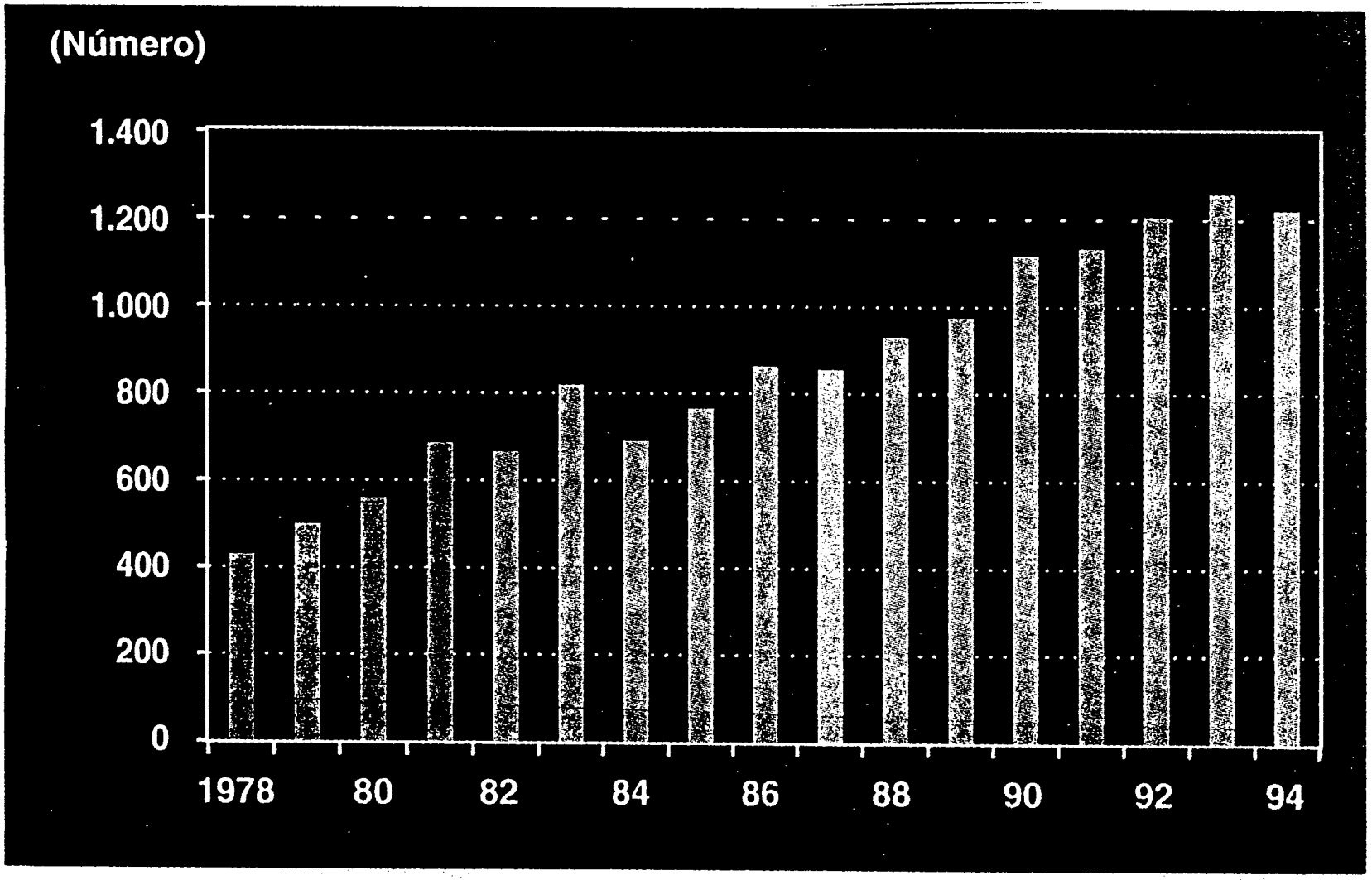
SOURCE: Data Base of Universities and CONICYT, Chile.
Note : Engineers working on R & D.

Academic Degree of the Staff at the Chilean Universities



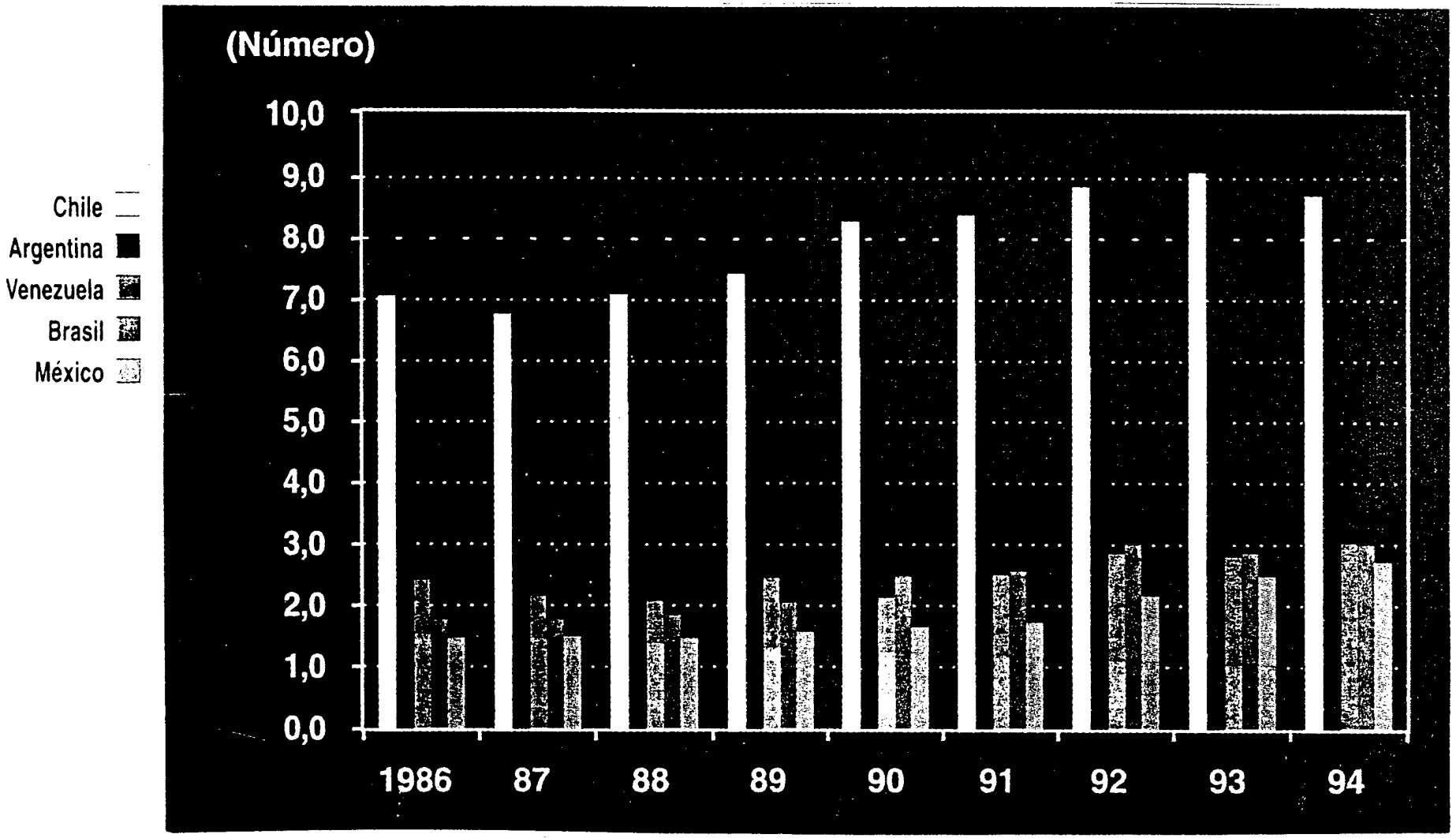
SOURCE: Data Base of Universities and CONICYT, Chile.

Number of Papers Produced in Chile and Published in Journal of Current Content



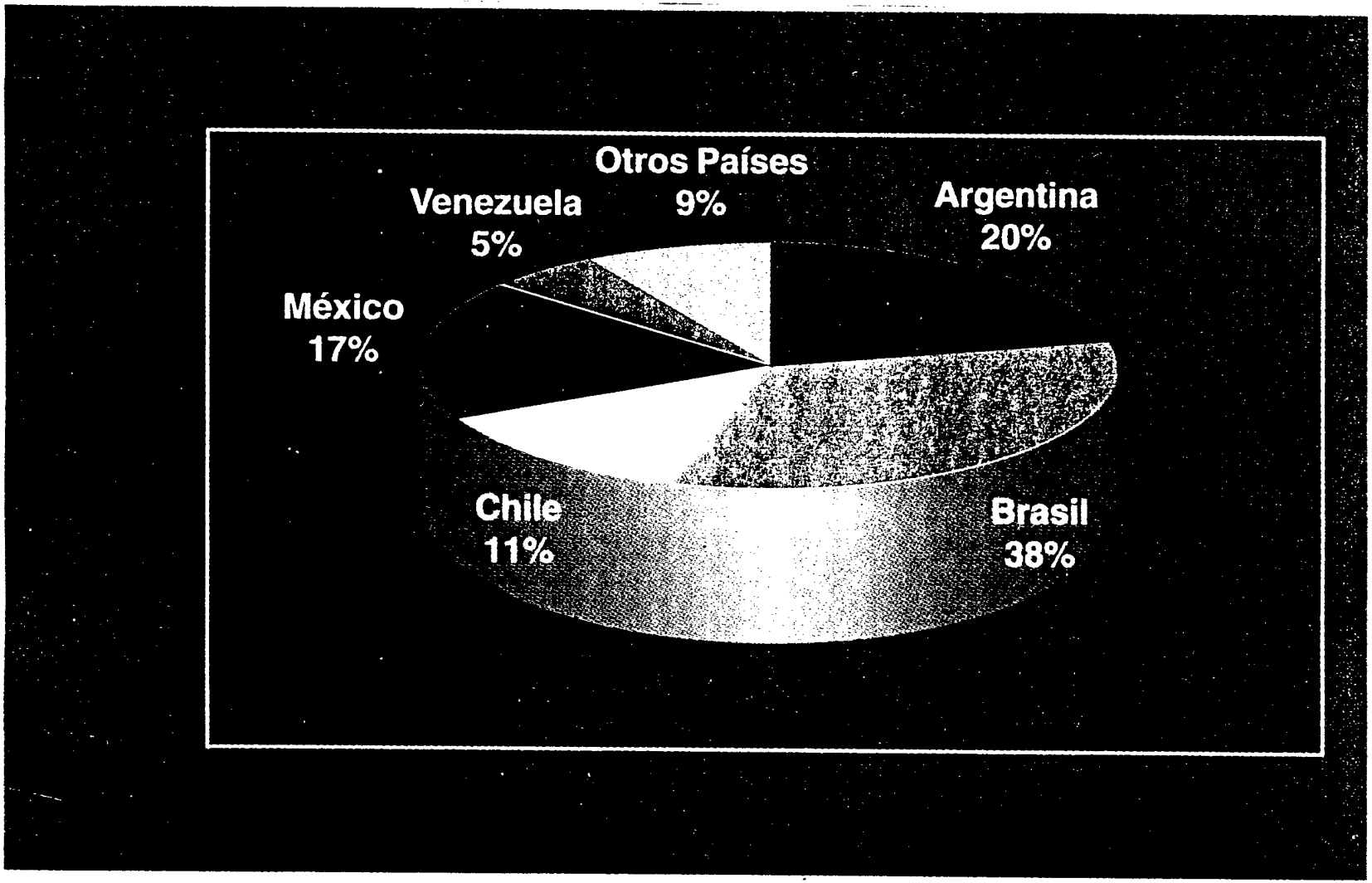
SOURCE: I.S.I.

Published Papers per 100,000 inhabitants



SOURCE: I.S.I.

Percentage of Papers Produced in Latin America (1986-1994)



SOURCE: I.S.I.

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Dr. Saravia received his B.S. in Electrical Engineering and Physics from the Universidad de Chile in 1981, and his PhD degree in Physics from the Rensselaer Polytechnic Institute in Troy, NY, in 1987. In 1985 he joined InterScience, Inc. , an R&D company at the Rensselaer Technology Park, where he became a senior scientist in 1988. At InterScience, Dr. Saravia was involved in several science and technology projects covering a broad range of applications including plasma physics, lasers and photonics, electromagnetics advanced electronic designs. At InterScience, Inc. Dr. Saravia was also a principal investigator and project manager in several SBIR Phase I and Phase II projects with the Department of Defense, Department of Energy, and NSF, and he was a key player in pushing forward some of these SBIR projects to the commercial market for the company. From 1993 Dr. Saravia worked as a scientific consultant for the Chilean Nuclear Energy Commission (CCHEN) and in March of 1994 he joined this Organization in Santiago, Chile. At CCHEN he is the principal science and technology advisor to the Executive Director and the President of the organization, in addition to his responsibilities as the chief of the Technology Transfer Department and Chief of the Lithium Program at CCHEN. He also interacts permanently with the Advisory Committee on Science and Technology to the Presidential and Parliamental Braches, as well as with CONICYT which is the National Commission for Science and Technological Research. Based on the extensive Experience gained over the years working in the United States, Dr. Saravia has played a very important and effective role in establishing collaboration programs in science and technology between CCHEN and laboratories and companies overseas, specially in the United States, Canada and Australia.

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